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FEASIBILITY OF DEVELOPING A TRIDEM AXLE TRACTOR FOR LOG-HAULING APPLICATIONS

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The contents of this report reflect the views of the Forest Engineering Research Institute of Canada (FERIC) and not necessarily the official views or opinions of the Transportation Development Centre of Transport Canada.

Un sommaire en français de ce rapport est inclus avant la Table des matières.

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16. Abstract

The feasibility of building a tractor truck with a tridem group of axles for log-hauling applications was investigated in a project undertaken by the Forest Engineering Research Institute of Canada (FERIC) under a contract with the Transportation Development Centre of Transport Canada. Literature and hardware searches were conducted. A traction/gradeability analysis and a vehicle dynamics investigation were undertaken through computer modelling and simulation. It was found that traction/gradeability could be significantly improved by using a tridem axle tractor unit. However, the vehicle dynamics study revealed performance deficiencies for some multi-articulation-point vehicles that use 3-axle tractors and these deficiencies are carried over to the 4-axle tridem tractor. In terms of a single-point articulated unit, the tridem tractor offers the benefits of improved traction in combination with the higher productivity that is currently available with multi-axle multi-articulated configurations used for log hauling. The report recommends the building and testing of such a vehicle.

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16. Résumé

La possibilité de réaliser un tracteur tridem pour le transport forestier a été étudiée dans le cadre d'une étude menée par l'Institut canadien de génie forestier aux termes d'un marché conclu avec le Centre de développement des transports de Transports Canada. Cette étude a comporté une recherche documentaire complétée par une recherche sur les matériels adéquats. La puissance de traction en palier et en rampe et la stabilité dynamique des tracteurs ont été analysées par modélisation informatique. La recherche a montré que l'essieu tridem permet d'accroître sensiblement la puissance de traction effective en palier et en rampe. Cependant, les études de comportement dynamique ont révélé des faiblesses dans le comportement de certains ensembles à remorques multiples que le tracteur utilisé soit de type tandem ou tridem. Un ensemble articulé à une seule remorque et tracteur tridem à voie large constitue une configuration apportant un gain dans la puissance de traction tout en assurant une productivité supérieure à celle des configurations multi-essieux à plusieurs remorques. Le rapport rendant compte de la recherche recommande la construction et l'essai d'un tel véhicule.

17. Mots clés	18. Diffusion
Tracteur tridem, tracteur à train roulant tridem, transport forestier, traction, traction en rampe, stabilité dynamique des poids lourds, transports, simulation informatique.	Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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Other individuals who made valuable contributions to this project include Dr. M. El-Gindy and John Woodrooffe of the National Research Council (NRC), and Jon Preston-Thomas of the Vehicle Systems Development Corporation (VSDC).

SUMMARY

As the distances between the timber resource and the processing mills have increased, log-hauling vehicle operators in the Interior of British Columbia have increased the payload capacity of their tractor/trailer combinations by adding more axles to the trailers to minimize transportation costs. The traction ability of the tractor unit in the off-highway segment of the hauling cycle is the limiting factor in more effectively implementing this strategy. Because a 4-axle tractor using a tridem axle group (i.e. a "tridem tractor") potentially offers improved traction ability over current 3-axle tandem drive tractors, a research project was undertaken to determine the feasibility of developing such a vehicle. The Western Division of the Forest Engineering Research Institute of Canada (FERIC), under a contract with the Transportation Development Centre of Transport Canada's Policy and Coordination Group, conducted a study with the following objectives:

- Evaluate the stability, traction, and operational productivity of the tridem axle group for log-hauling tractors.
- Investigate a means of improving the braking safety of log-hauling vehicles that operate on public highways.
- Examine the possibility of developing a log-hauling vehicle that would be less damaging to the pavement on public highways.
- Investigate the possibility of improving the off-highway tractive ability of log-hauling vehicles.
- Demonstrate and evaluate new technology for the log-hauling industry.

The first phase of the research, conducted in 1988-89, comprised three tasks: a literature search and a hardware search, a traction and gradeability study, and a vehicle dynamics analysis.

The literature search revealed little in the way of previous research in the use of tridem axle groups for use on Class 8 tractor units. North American axle manufacturers do not produce a tridem drive axle group that is suitable for this application in terms of balanced interaxle torque distribution, steering ability, and track width. However, the hardware search did determine that appropriate componentry exists for building a tridem axle group consisting of an airlift non-drive axle located forward of a tandem drive axle assembly. The technology is also available to ensure that equalized axle loading within the tridem axle group is achieved according to the guidelines of Roads and Transportation Association of Canada (RTAC). (RTAC is now known as the Transportation Association of Canada (TAC).)

A traction/gradeability study conducted through computer modelling indicated that dramatic improvements could be achieved by a tridem tractor unit over the existing tandem drive axle configurations of comparable GVW. The greatest improvement was realized by a tridem tractor with the airlift axle in the raised position.

Computer modelling was used to study the vehicle dynamics of conventional tandem axle tractor/trailer log-hauling combinations as well as potential tridem axle tractor/trailer combinations. Because of the unique design features of these vehicles and the absence of suitable computer simulation models to predict their directional dynamics, it was necessary to develop three new linear yaw plane mathematical models for this study. Vehicle static roll stability was analyzed using the University of Michigan Transportation Research Institute's (UMTRI) Static Roll Model, with some modifications to the input/output codes.

The vehicle combinations examined in this study have been evaluated against the performance criteria of rollover threshold, response time, understeer coefficient, offtracking indicator, and rearward amplification. The study indicated significant performance deficiencies with respect to two

of the existing combinations, namely the tractor/jeep/pole trailer and the tractor/quadaxle trailer. These combinations were also found to be deficient when modelled with a tridem tractor. However, the 6-axle tridem tractor/pole trailer combination was found to perform satisfactorily and to offer a viable alternative to the existing 6-axle tractor/jeep/pole trailer combination.

SOMMAIRE

A mesure que les distance séparant les sites d'exploitation forestière des scieries se sont accrues, les entreprises de transport forestier de la Colombie-Britannique ont cherché à augmenter la productivité de leurs opérations en utilisant des véhicules articulés avec plus d'essieux. Or le succès d'une telle stratégie repose sur un facteur déterminant qui est la puissance de traction hors routes disponible. Etant donné que le tractor tridem, c'est-à-dire à 4 essieux dont 3 sont moteurs, dispose en théorie d'une puissance de traction supérieure à celle des tracteurs à 3 essieux (1 directeur et 2 moteurs), une recherche a été lancée sur la possibilité de développer un tracteur tridem pour cet usage. Aux termes d'un marché conclu avec le Centre de développement des transports, Groupe des politiques et de la coordination, Transports Canada, la division Ouest de l'Institut canadien de génie forestier a mené une étude avec les objectifs suivants :

- Évaluer les caractéristiques de stabilité, de traction et d'exploitation d'un tracteur tridem pour les besoins du transport forestier;
- Trouver le moyen d'améliorer la sécurité en freinage des véhicules de transport forestier lorsqu'ils circulent sur les voies publiques;
- Évaluer la possibilité de réaliser un véhicule de transport forestier moins agressif vis-à-vis la chaussée des voies publiques;
- Approfondir la possibilité de relever la puissance de traction hors routes d'un tel véhicule;
- Évaluer les technologies nouvelles pouvant trouver des applications dans ce domaine et les soumettre à des expérimentations en service.

La phase I de la recherche, menée en 1988-1989, a comporté les trois tâches suivantes : recherche documentaire et de matériels adéquats, recherche sur la traction en palier et en rampe, et analyse de la stabilité dynamique.

La recherche documentaire a révélé fort peu d'études antérieures en matière de tracteurs classe 8 équipés en tridem. Aucun des constructeurs nord-américains ne produit des trains roulants tridem répondant aux exigences de bonne distribution des efforts entre les essieux moteurs, de pilotabilité et de largeur de voie. Elle a quand même montré qu'il est possible de réaliser un train tridem formé d'un train tandem précédé d'un essieu porteur relevable, garantissant une bonne distribution des efforts entre ces trois essieux, selon les exigences de l'Association des transports du Canada.

La recherche sur la traction en palier et en rampe par voie de modélisation a montré que le tracteur tridem possède des caractéristiques bien supérieures aux tracteurs tandem actuels, à poids total en charge comparable, surtout avec l'essieu relevable en position levée.

La stabilité dynamique des tracteurs tandem actuels, et celle des tridem à l'étude, en traction de semi-remorques chargées a été étudiée par modélisation informatique. Or vu les caractéristiques particulières de ce type de véhicules ainsi que l'absence de logiciels adéquats, il a été nécessaire d'élaborer trois nouveaux modèles linéaires permettant d'analyser le comportement en lacet de ces véhicules. Quant à leur stabilité en roulis, elle a pu être analysée grâce au modèle élaboré par le Transportation Research Institute de l'Université du Michigan, après certaines modifications apportées aux codes entrée-sortie.

L'analyse des combinaisons étudiées a été faite en fonction des critères d'appréciation suivants : accélération latérale maximale admissible, temps de réponse, coefficient de sous-virage, indicateur de déport latéral et amplification du mouvement de lacet à l'arrière. La recherche a mis en évidence la grande faiblesse inhérente de deux combinaisons couramment utilisées, à savoir le tracteur/diabolo tracté/semi-remorque à poutre télescopique et le tracteur/semi-remorque 4 essieux. La modélisation

a également mis en évidence les faiblesses de ces deux combinaisons lorsqu'elles sont attelées à un tracteur tridem. Par contre, la combinaison tracteur tridem/semi-remorque à poutre télescopique totalisant 6 essieux a montré de bonnes caractéristiques et pourrait remplacer avantageusement la combinaison couramment utilisée tracteur/diabolo tracté/semi-remorque à poutre télescopique qui totalise également 6 essieux.

Table of Contents

	Page
INTRODUCTION	1
Background	1
Project Objectives	2
STUDY METHODOLOGY	2
Phase I Tasks	2
Subcontractors	2
Study Assumptions	3
RESULTS AND DISCUSSION	4
Literature Search and Hardware Search	4
Traction/Gradeability Algorithm	6
Results of Traction/Gradeability Analysis	7
Development of Dynamic Performance Models	8
Performance Criteria for Static Rollover and Dynamic Performance Models	9
Static Rollover Threshold	9
Directional Dynamics	10
Results of Static Rollover and Dynamic Performance Analyses	11
Static Rollover Threshold	11
Directional Dynamics	13
CONCLUSIONS	16
Literature and Hardware Searches	16
Traction Gradeability Study	16
Dynamic Performance Analysis	17
RECOMMENDATIONS	18
LIST OF REFERENCES	19
APPENDICES	
A Representations of the Block Load Densities as Applied to Various Log-Hauling Vehicle Combinations	A-1
B Subject Tractor Units for Field Testing	B-1
C Organizations Consulted During the Hardware Search	C-1
D Log-Hauling Routes with Challenging Grades	D-1
E Log-Hauling Vehicle Combinations Analyzed for Dynamic Performance and Static Roll Stability	E-1

LIST OF TABLES

	Page
1. Gross Vehicle Weights Used in the Analysis	4
2. Gradeability Improvement Summary	8

LIST OF FIGURES

	Page
1. Basic tridem axle group proposals	1
2. Compensating reach coupling arrangement	3
3. Equalized load-sharing concern of an add-on air-spring suspended axle	5
4. Gradeability of various 6-axle combinations (GVW about 49 000 kg) on a surface with a friction coefficient of 0.2 and a rolling resistance coefficient of 0.01	7
5. Gradeability of various 7-axle combinations (GVW about 57 000 kg) on a surface with a friction coefficient of 0.2 and a rolling resistance coefficient of 0.01	8
6. Influence of tractor type on rollover threshold with various trailers	11
7. Comparison of centre of mass locations: Tractor/jeep/pole trailer (top) and tractor/quadaxle trailer (bottom)	12
8. Influence of tractor type on the payload rearward amplification with various trailers at 90 km/h	13
9. Influence of tractor type on transient response time with various trailers	14
10. Influence of tractor type on the understeer coefficient with various trailers at 90 km/h	15
11. Influence of tractor type on the highspeed offtracking with various trailers at 90 km/h	16

INTRODUCTION

Background

As the timber resource in the Interior of British Columbia has become poorer in quality and more distant from the mills, log-hauling transportation costs have risen to the point where they are the highest component of the cost of supplying wood to the mills. The log-hauling contractors, who operate about 2500 trucks in the Interior of British Columbia, have attempted to reduce transportation costs by adding axles to the trailers to increase the legal payloads. However, with increased payloads and the mills insisting that logs be hauled with all butts facing forward, the ability of the tractor to pull the trailer has decreased, the braking effectiveness of the tractor has diminished, and the potential for damaging the road surface has increased. Efforts to reduce loading on the drive axles of the tractor by modifying the load configuration have not been successful. Consequently, log-hauling vehicles continue to operate with limited tractive ability during the off-highway portion of the haul route, and with overloaded drive axles and reduced braking effectiveness during both the on-highway and off-highway portions.

In response to these problems, the Forest Engineering Research Institute of Canada (FERIC) initiated an 18-month study in the fall of 1988 in conjunction with E.H. Borrow Log Hauling and Weldwood of Canada Limited, both located in Williams Lake, British Columbia. Funding for this project was provided by the Transportation Development Centre of Transport Canada and the Ministry of the Solicitor General of British Columbia.

Use of a tridem axle group on the tractor (referred to here as a tridem tractor) was expected to lead to improved traction, reduced drive-axle loading, and increased braking effectiveness. Two basic tridem axle configurations were considered (Figure 1): a tridem axle group consisting of one non-driven lifting axle and two driven axles, and a tridem axle group with all axles driven and non-lifting.

In the case of the lifting-axle proposal, the airlift axle would be in the up position during the return-empty trip (from the mill to the logging site), and for that part of the loaded trip (from the logging site to the paved highway) travelled on a gravel or snow-covered off-highway road. This would permit maximum tractive effort where it is most needed, i.e. on the unpaved off-highway portion of the duty cycle.

In the case of the fixed tridem drive axle proposal, the improved torque distribution was expected to have tractive benefits similar to those provided by the lift-axle concept. Improvements in braking effectiveness and axle loadings were also expected to be the same.

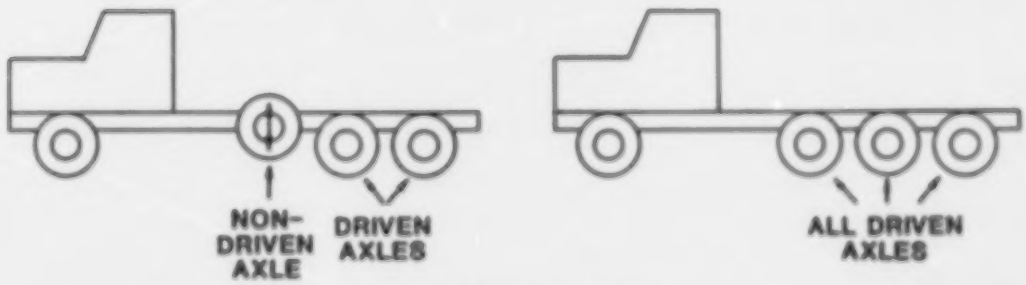


Figure 1. Basic tridem axle group proposals. Left, the lifting-axle proposal. Right, the fixed tridem drive axle proposal.

The research plan was divided into two phases. Phase I, described in this report, reviewed existing technology and analyzed the expected dynamic behaviour of new tridem tractor options through computer modelling; Phase II, yet to be initiated, would build and demonstrate the tridem tractor option that ranked highest during the Phase I analysis provided its simulated performance was acceptable.

Project Objectives
The Phase I objectives were:

- Review the research work undertaken to date that would assist in the design of a tridem tractor.
- Determine the componentry appropriate for consideration in the construction of a tridem tractor.
- Develop a traction/gradeability algorithm that can quantitatively rank the performance of existing log-hauling combinations, and predict the performance of the proposed tridem axle tractor configurations.
- Develop dynamic performance computer models to rank the performance of existing tandem axle tractor/trailer log-hauling combinations, predict the performance of the tridem axle tractor/trailer combinations, and establish the acceptability of their performance in terms of: static and dynamic rollover; tire/pavement friction demand; and low-speed, high-speed, and transient off-tracking.
- Identify and prepare detailed specifications of the tridem tractor axle configuration(s) for field appraisal in Phase II.

The Phase II objectives are to:

- Construct a tridem tractor unit.
- Demonstrate axle-load equalization within the tridem axle group.
- Conduct a 12-month demonstration of the vehicle in revenue service. This would be an appraisal period with specific attention given to dynamic performance, maintenance costs, operational costs, and productivity gains.

The prerequisite to initiating Phase II is that results of Phase I justify continuing to the construction and test stages.

STUDY METHODOLOGY

Phase I Tasks
Phase I included three basic tasks: a literature search and a hardware search, the development of a traction/gradeability algorithm for computer modelling, and the development of a dynamic performance simulation program. Throughout Phase I, computer modelling was used to evaluate a wide variety of axle and suspension componentry for use on two different tridem axle configurations.

Subcontractors
The development of the traction/gradeability algorithm was undertaken by the Vehicle Systems Development Corporation (VSDC) of Ottawa who are expert in the field of terramechanics and vehicle mobility. VSDC developed a procedure for evaluating the gradeability of log-hauling vehicles that considers the drive axle arrangements of the tractor and the various multi-axle trailer types, the effects of interaxle coupling, axle differential, suspension, and the vehicle's tire configurations. The computer model was used to predict the gradeability of tandem drive axle tractors, tridem drive axle tractors, and tridem tractors with a non-driven lift axle. In addition, the model can accommodate two-, three-, and four-axle trailers, including jeeps, to be studied in combination with any of the three aforementioned tractor types.

The various existing log-hauling tractor/trailer combinations were then ranked with respect to

gradeability performance, and the different tridem tractor options were also included in this ranking by means of the computer model.

The compensating reach between the tractor and trailer is the typical coupling arrangement for British Columbia log-hauling vehicles (Figure 2). The unique coupling feature of this compensating hitch prevented the use of existing computer simulation models to predict the dynamic or directional behaviour of any of these vehicles. This required the development of three new mathematical models to examine the transient, steady-state, and frequency response characteristics of these tractor/trailer combinations. The rollover threshold could be determined for most log-hauling configurations by using the previously developed University of Michigan Transportation Research Institute (UMTRI) Static Roll Model (1).[1] The National Research Council (NRC) was contracted to do this development and simulation work through its Vehicle Dynamics Laboratory in Ottawa.

A performance ranking of existing tractor/trailer combinations was established by means of the following analytical methods:

- Geometrical analysis.
- Time histories of response to steering input (in the yaw plane motions).
- Frequency response analysis.
- Static rollover threshold analysis.

Subsequently, this ranking was used as the reference to which the tridem tractor proposals were compared.

Study Assumptions

Log payload for each of the tractor/trailer combinations was represented by a uniform block load density. Block load density varies significantly with wood density and log diameter. It is defined as:

$$\text{block load density} = \frac{\text{net load weight}}{\text{load width} \cdot \text{load silhouette area.}}$$

A block load density of 390 kg/m^3 was determined to be representative of the loads carried in the Williams Lake area of British Columbia (test site proposed for the Phase II field trials). This value was used consistently by all researchers in their respective calculations.

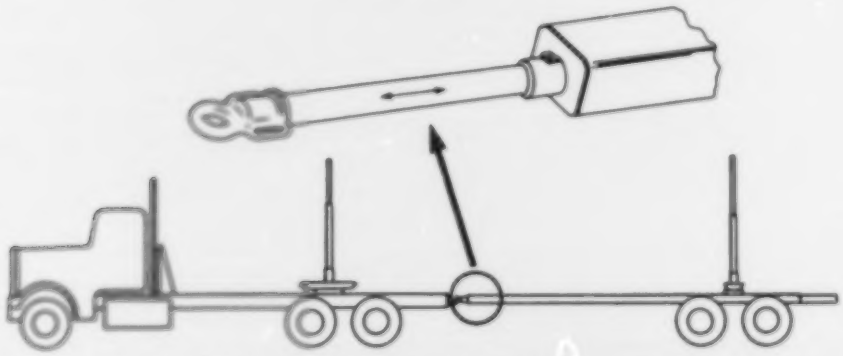


Figure 2. Compensating reach coupling arrangement.

[1] Numbers in brackets designate references listed at the end of this report.

All of the six tractor/trailer combinations shown in Appendix A were assumed to utilize a load length of 20.1 m, a load width of 2.4 m, a front bunk height of 1.47 m, and a rear bunk height of 1.45 m.

The front and rear load heights for each combination were selected to provide the required maximum axle loads within legal limits, while ensuring that the load height did not exceed the legal maximum of 4.15 m and that the gross vehicle weight (GVW) did not exceed the maximum legal limits in British Columbia (2). Table 1 lists the GVW amounts that were used in this study for the various configurations.

It was assumed that all three axles of the tridem group would exhibit equalized load sharing and, in the case of an airlift axle, the controls will not be accessible to the driver from the truck cab. In addition, any control must be of the up/down type with down pressure being automatically adjustable to ensure equalized load sharing within the tridem group. When the vehicle is loaded, the airlift axle would be up only during the off-highway segment of the route because this is generally when the traction demand is greatest.

Although one other tractor wheelbase (6.2 m) was studied in Phase I, the subject vehicle for field evaluation was a C500 Kenworth and is described in both a tandem arrangement (wheelbase 6.7 m) and a tridem arrangement (wheelbase 6.0 m) in Appendix B. The tractor with the 6.2-m wheelbase was included as an addition to the study because it conforms to the maximum wheelbase guidelines of Roads and Transportation Association of Canada (RTAC) (3). (RTAC is now known as the Transportation Association of Canada (TAC).)

Table 1. Gross Vehicle Weights Used in the Analysis [a]

Tractor type	Trailer type			
	Pole (kg)	Jeep/pole (kg)	Triaxle (kg)	Quadaxle (kg)
Existing tandem	40 844 (5)	48 973 (6)	49 519 (6)	58 501 (7)
Tridem	48 099 (6)	52 230 (7)	55 888 (7)	63 500 (8)

[a] The number in parentheses indicates the number of axles in the combination.

RESULTS AND DISCUSSION

Literature Search and Hardware Search

A literature search and a hardware search were conducted to determine the status of drive axle and suspension technology and the relevance of that technology to the project. Both searches revealed that few advancements have been made in the area of tridem drive axle technology for Class 8 highway vehicles. North American axle manufacturers, such as Eaton and Rockwell, have produced tridem drive axle systems in the past, but without a balanced torque distribution from axle to axle. They have used a conventional tandem drive torque divider in the most forward differential which yields a torque distribution of 50% in the first axle, 25% in the second, and 25% in the third. While some European tridem drive axles (such as those manufacturered by GKN) address the need for balanced torque distribution, they are designed for military applications and require such unconventional components as "super-single" wide-base tires, specialized frame attachments, and unique suspensions.

The concept and application of tridem drive systems in North America is at least fifteen years old and is predominantly found in the redi-mix concrete industry. Users report two specific problems. First, the suspension plays a crucial role in the performance of tridem drive axles and individual axle spin-out is often experienced on "walking-beam" systems. To overcome this, operators lock out the interaxle and individual axle differentials; this increases drive-line stress and accelerates tire wear. Second, the aligning moment generated by the three locked rear axles creates an understeer situation (at moderate levels of lateral acceleration) that negatively influences vehicle maneuvering. The magnitude of understeer at a given speed is a function of weight distribution, tire characteristics, and wheelbase.

Very few available tridem drive suspensions provide equal axle loading. Tridem walking-beam assemblies are available, but their limited vertical axle travel restricts their application for log-hauling vehicles. Air-spring suspensions show the greatest promise for tridem drive axle application; in some cases these can be "stiffened in-roll" to enhance vehicle roll stability for the high centre of mass that is characteristic of log-hauling vehicles.

The addition to a tandem drive axle assembly of a non-driven third axle in either the pusher location (forward of drivers) or tag location (rearward of drivers) is not a new concept. However, the independent suspension of the third axle does not readily provide for true load sharing with the two driven axles. Most log-hauling vehicles in British Columbia use a tandem drive axle walking-beam suspension. Combining this suspension with an air-spring add-on axle suspension does not satisfy the criteria of equalized load sharing (Figure 3). Some recent hardware developments hold promise of achieving this, but remain to be appraised in the field.

Both the non-driven third axle group and the all-driven tridem axle group influence vehicle steerability through their increased aligning moments. Self-steering, non-driven, third axles are one potential solution. With this option, however, the numerous surface irregularities typical of off-highway roads present major concerns for dynamic stability. An operator-controlled steerable axle, either driven or non-driven, would provide a more stable alternative, but such componentry is not currently available.

To ensure acceptance of any tridem configuration by industry, the hardware search was influenced by (but not restricted to) the following considerations: any new hardware should be compatible with existing equipment, e.g. tires and rim sizes; the additional weight of the tridem axle assembly should be kept within reasonable limits; the add-on hardware should be domestically supported; and the additional costs of the tridem components should be reasonably affordable.

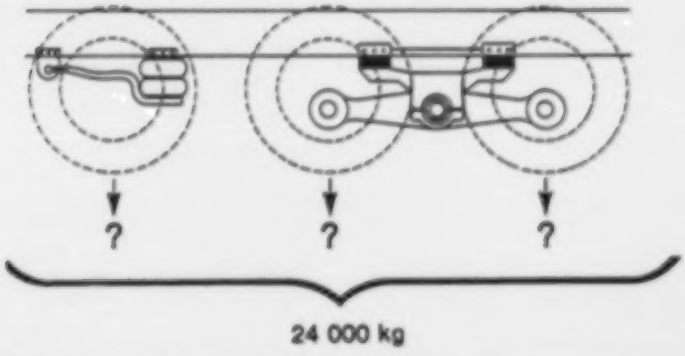


Figure 3. Equalized load-sharing concern of an add-on air-spring suspended axle.

Appendix C summarizes the end users, manufacturers, and suppliers that were contacted in the hardware search portion of this project.

The literature and hardware searches revealed the following:

- A full air-spring suspension for the tridem group has the most promise for equalized axle load sharing, but it presents concerns regarding roll stiffness.
- The equalized axle load sharing ability of a combined air/walking-beam tridem suspension is theoretically possible, but it would require the use of untried control hardware.
- Dual-tired, non-driven or driven, forced-steer axles are not available for this application.
- With the airlift axle in the "up" position, a tandem axle walking-beam assembly would be loaded to 23 000 kg; this necessitates use of a suspension and drive axle assembly with a higher load rating than is commonly required and these are readily available.
- At this time, there are no North American tridem drive assemblies that evenly distribute torque.
- The Roads and Transportation Association of Canada (3) recommended wide-tracking tandem drive axle assemblies (2.6-m overall width) be used, and these are now available as an effective means of improving the roll stability for Class 8 vehicles.
- To improve traction performance over the existing tandem drive tractors (4 x 6), driven steering axles (6 x 6) are available. At least one axle manufacturer has eliminated the need for a transfer case to drive the steering axle, thus reducing tare weight. Further, the 10% adverse grades generally encountered do not cause a significant shift in weight from the steering axle such that tractive ability would be reduced.
- Two relatively new methods of improving traction are emerging and bear investigation beyond the scope of this project. Automatic spin regulation (ASR) is an option on vehicles equipped with the antilock brake systems; central tire inflation (CTI) adjusts tire inflation pressures in accordance with speed, traction, and load requirements while the vehicle is in motion.

Traction/Gradeability Algorithm

One of the main objectives of this project was to define a vehicle with improved tractive ability for the off-highway portion of the log-hauling route. Vehicle Systems Development Corporation was contracted to provide a computer simulation model that would predict the traction-limited gradeability of the various existing and proposed tridem log-hauling combinations. This work was restricted to ice and snow-packed road surfaces because these conditions present the greatest traction challenge to the equipment. The traction/gradeability algorithm results are applicable to ice and snow-covered roads only and may not be directly applied to other traction-limiting situations such as wet or muddy road conditions.

Preston-Thomas and Wong (4) describe the traction-related computer modelling that was undertaken in support of this project. A computer simulation model was developed to predict the gradeability of a number of tandem tractor/trailer and tridem tractor/trailer combinations for log-hauling. The model assumes that the gradeability of the various combinations is traction-limited rather than power-limited. As such, it takes into account the basic two-dimensional geometric features of the various vehicle combinations, along with the effects of suspension characteristics on load distribution, and it assumes that the rolling resistance and the tractive effort of the vehicles are proportional to tire load. The basic output of the model includes the equilibrium grade (i.e., the maximum grade that the vehicle can climb with the assumed coefficients of friction and rolling resistance), and the various axle-load and thrust distributions.

This first phase of work also required the identification of log-hauling routes that present a challenge to the gradeability and handling of existing tractor/trailer combinations. Three such road segments were selected in the Williams Lake area and Appendix D highlights the grades, alignments, and geographic locations of each. The forest industry in the Interior of British Columbia

generally attempts to limit sustained sections of adverse road to a maximum of 8%. Short intervals of road often exceed this maximum. Construction of road curves is generally dictated by topography with the minimum radius being approximately 20 m.

The tridem gradeability analysis (4) of the Phase I work has provided a gradeability ranking of the existing log-hauling tractor/trailer combinations as a baseline reference against which any tridem tractor options can be compared. From this comparison, the relative improvement in gradeability that the two tridem tractor options offer can be determined, thereby identifying the one with greatest traction ability. To properly conduct this comparison, it was necessary to group the various tractor/trailer combinations according to common gross vehicle weight (GVW) which also happens to group the vehicles by their number of axles. Figure 4 illustrates the gradeability of four 6-axle combinations having a GVW of about 49 000 kg, and Figure 5 compares three 7-axle combinations with GVWs in the order of 57 000 kg.

Results of Traction/Gradeability Analysis

Figures 4 and 5 illustrate that significant improvements in gradeability can be realized with a tridem tractor, as compared to the existing tandem tractor units. In the 6-axle combination group illustrated in Figure 4, the tridem drive tractor/pole trailer exceeds the gradeability of a tandem tractor/triaxle trailer and tandem tractor/jeep/pole trailer by 37.3% and 29.5% respectively. In the same figure, a tridem tractor/pole trailer with a lift axle demonstrates the greatest improvement in gradeability, namely 56.7% more than a tandem tractor/triaxle trailer and 47.9% more than a tandem tractor/jeep/pole trailer. Figure 5 illustrates a similar ranking of the tridem options in the 7-axle category.

Under identical conditions a 5-axle combination (tandem tractor/tandem pole trailer) with a GVW of about 40 000 kg was found to have a gradeability of 7.9%. However, 6- and 7-axle combinations are more common today because of their extra payload capacity, and, as a consequence of this greater capacity, they also have less gradeability.

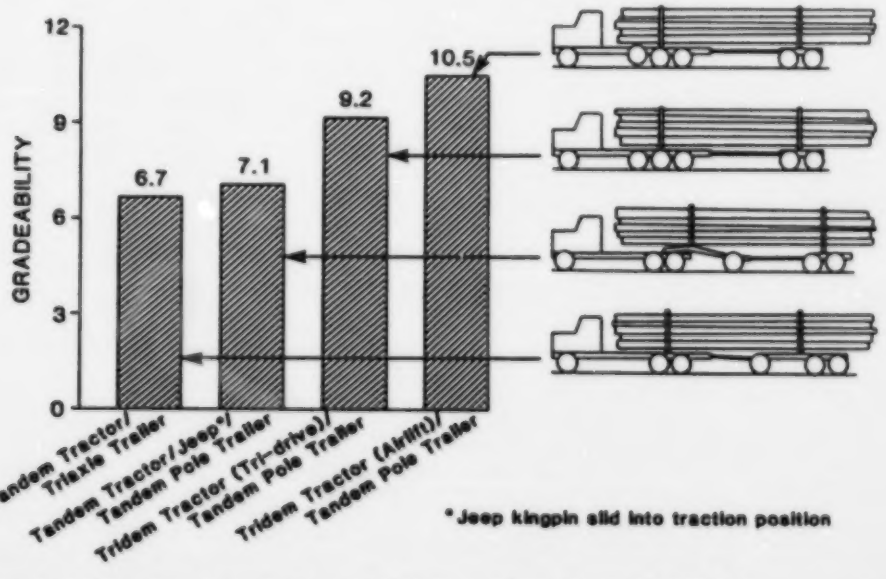


Figure 4. Gradeability of various 6-axle combinations (GVW about 49 000 kg) on a surface with a friction coefficient of 0.2 and a rolling resistance coefficient of 0.01.

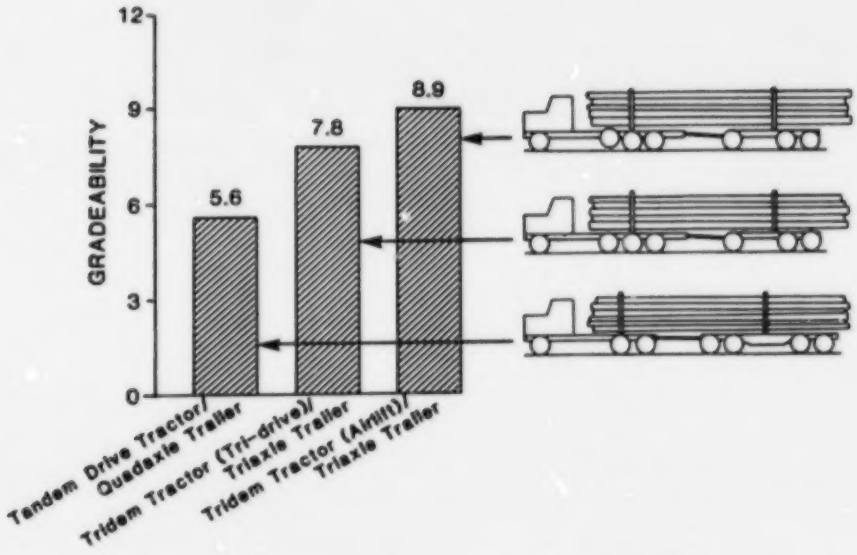


Figure 5. Gradeability of various 7-axle combinations (GVW about 57 000 kg) on a surface with a friction coefficient of 0.2 and a rolling resistance coefficient of 0.01.

Table 2. Gradeability Improvement Summary

Total number of axles	Existing baseline combinations	Improvement in gradeability with tridem options
6	Tandem tractor/triaxle trailer	37.3% Tractor/pole trailer with tri-drive 56.7% Tractor/pole trailer with lift axle up
6	Tandem tractor/jeep/pole trailer	29.5% Tractor/pole trailer with tri-drive 47.9% Tractor/pole trailer with lift axle up
7	Tandem tractor/quadaxle trailer	39.3% Tractor/triaxle trailer with tri-drive 58.9% Tractor/triaxle trailer with lift axle up

Table 2 summarizes the results of the traction/gradeability computer simulations. The results clearly indicate that the tridem tractor option employing the liftable nondrive axle is the most beneficial in terms of traction performance. To achieve this level of improvement, most of the 24 000 kg maximum weight legally carried on the highway by the tridem group is transferred onto the two drive axles by lifting the non-driven third axle during the off-highway portion of the route.

Development of Dynamic Performance Models

The NRC, through its Vehicle Dynamics Laboratory in Ottawa, was contracted by FERIC to conduct a computer simulated analysis of the dynamic performance of these log-hauling vehicles. UMTRI has developed models over the last 15 years for studying conventionally articulated heavy vehicles (1).

With one exception, the UMTRI models, referred to by name as Yaw/Roll, Phase 4, Simplified (Kinematic) Off-Tracking, and Simplified Braking Simulation, *cannot be used or modified* to evaluate the dynamic performance of most British Columbia log-hauling vehicles because of the unique design features of these vehicles. These unique features include a sliding pole drawbar constrained by a fixed bunk separation, and the number of articulation points exceeding the number of the joined units (these include logging tractor, jeep, dolly, and trailer). For this reason, NRC's initial task was to undertake a geometrical analysis of the various vehicle combinations to determine the interacting relationships of the various joined units within a given combination. This geometrical analysis was fundamentally important because it was necessary to solve the equations of motion which had been developed in the study to represent the existing and proposed vehicle combinations. Three new yaw plane mathematical models were subsequently developed by NRC to examine the transient, steady-state, and frequency response of these vehicles. The models individually describe the dynamics of one of the following groups of log-hauling combinations: tractor/pole trailer, tractor/jeep/pole trailer, and tractor/triaxle or quadaxle trailer. An NRC report (1) published under this contract details this work.

The Static Roll model is the only UMTRI model used by NRC in this study. It was designed for the purpose of predicting the rollover threshold of a tractor/semitrailer combination, but the model can be used to predict the rollover threshold of the following vehicle combinations: tractor/pole trailer, tractor/triaxle trailer, and tractor/quadaxle trailer. However, caution is required in applying the definition of the rollover threshold—i.e. for the purposes of this project the static rollover threshold was defined as the point at which a single group of axles completely lifts, rather than the point at which all axles have lifted—and in entering the required data to this model. Using this model, NRC has examined eighteen log-hauling combinations with a 2.4-m track width, and twenty-four log-hauling combinations with a 2.6-m track width. This examination required 42 input data files, each describing a specific combination.

The tractor/jeep/pole trailer combination was not included in the static roll portion of the study because the UMTRI model cannot accommodate the combined features of the jeep's bunk loading and coupling arrangements. Despite this limitation, the rollover threshold and the related centre of mass height location of this combination were otherwise addressed in the study.

The creation of the models needed to evaluate dynamic rollover threshold and braking efficiency are beyond the resources of this project. To study the dynamic rollover threshold of these vehicles would require building a new three-dimensional mathematical model (similar to Phase 4 or Yaw/Roll) for each vehicle combination. NRC predicts that 3-4 man-years of development and validation work would be required to provide dynamic rollover models for log-hauling vehicles. New mathematical models created from first principles are required to determine braking efficiency for log-hauling vehicles. Complete and accurate measurements of the brake components are required to determine their operational characteristics. Again, a substantial effort would be needed to model the various types of British Columbia log-hauling vehicles. It should also be mentioned that because of variations in brake-component characteristics, such as friction materials, mechanical linkages, and pneumatic actuators, validation of such models would be very difficult. Furthermore, a general model covering all aspects of vehicle dynamics and performance measures for all the log-hauling combinations could be developed over the next few years, but such a program would be too complex to run on current personal computers.

Performance Criteria for Static Rollover and Dynamic Performance Models

To justify proceeding to Phase II of the project, the performance of any acceptable tridem tractor is, in general, required to exceed the performance of the baseline vehicles.

Static Rollover Threshold. The rollover threshold of a vehicle is determined by calculating the lateral acceleration force (in units of g's) that is achieved immediately prior to one group of

composite axles on one side of the vehicle completely lifting off the ground. This criterion defines the maximum severity of steady state turn which a vehicle can tolerate without rolling over. The RTAC *Vehicle Weights and Dimensions Study: Technical Steering Committee Report* (3) indicates that, in general, loaded vehicles exhibit rollover threshold values in the range of 0.25 to 0.40 g and goes on to recommend a target performance level of 0.40 g or better.

Directional Dynamics. The evaluation of a vehicle's directional dynamics is based on four selected performance criteria. For each criterion, a suggested preliminary value represents the expected safe limit based on prudent engineering judgment and accepted international standards (e.g., the Bosch *Automotive Handbook* (5) was the basis for establishing the reaction time for the recommended range of transient response times).

Two analytical methods were used to predict directional dynamic performance in relation to the selected criteria. The first method, the Frequency Response Analysis, is employed to determine the rearward amplification during sinusoidal steering maneuvers. The second method, the Time Histories of Yaw Plane Response to Steering Input, is used to determine the vehicle's performance with respect to transient response time, understeer coefficient, and highspeed offtracking; a ramp-step steer or J-turn maneuver is modelled to determine these values. These four performance criteria are defined as follows:

• *Rearward Amplification (RWA)* is the ratio between the peaks of the lateral acceleration of the payload centre of gravity and the tractor centre of gravity during sinusoidal steering maneuvers (recommended performance range is from 1 (or less) to about 2), i.e.:

$$\text{RWA} = \frac{\text{lateral acceleration at centre of gravity of a towed unit}}{\text{lateral acceleration at centre of gravity of the tractor.}}$$

• *Transient Response Time* is the time required to reach 90% of the vehicle's steady-state lateral acceleration at highway speed (90 km/h) resulting from a rapid ramp-step steering input of maximum 1° and a steering rate of 5°/s. The acceptable range of response time depends upon personal and external factors affecting the driver. (Recommended range is from 0.3 to 1.7 s.)

• *Understeer Coefficient* is defined as:

$$\frac{\frac{\text{wheelbase}}{\text{turn radius}} - \text{front wheel steer angle}}{\text{steady-state lateral acceleration.}}$$

Negative values indicate understeering, and positive values indicate oversteering characteristics. The values do not depend on the lateral acceleration level because of the linearization of the yaw plane models. The values are valid for low-level lateral acceleration (less than 0.2 g). (Recommended performance range is from -4.0 to zero.)

• *Highspeed Offtracking Indicator* is defined as:

$$\frac{\sum_{n=1}^{N} \text{articulation angles}}{\text{dimensionless path curvature of tractor}}$$

where

N = number of articulation points, and

$$\text{path curvature} = \frac{\text{wheelbase}}{\text{steady state turning radius.}}$$

The above values are taken for a speed of 90 km/h and a front-wheel steering angle of 1°. (Recommended performance range is from zero to 2.5°.) In this case, the performance indicators serve to yield a relative determination of ranking of how the various vehicles under study offtrack with respect to one another. The expected safe maximum limit of 2.5° is the recommended parameter applied to this criterion and is based on the preliminary modelling estimates in lieu of other values being available.

Results of Static Rollover and Dynamic Performance Analyses

The study undertaken by NRC in support of this project included a greater variety of wheelbases and tridem add-on axles than is presented in these results. This occurred because initially all reasonable options were explored, and as the project evolved many considerations were eliminated because of unacceptable simulated performance.

This process has identified a single tridem tractor configuration as the most appropriate potential test vehicle. The specific vehicle has a 6.0-m wheelbase, a track width of 2.6 m, and a non-driven pusher axle to make up the tridem grouping. It is presented in these results as the only tridem tractor to be compared to the existing tandem drive baseline configurations in terms of the performance criteria.

Static Rollover Threshold. The modelling results illustrated in Figure 6 indicate that the existing log-hauling vehicles are at the low end of the 0.25 to 0.40 g range that is generally characteristic of on-highway loaded trucks (3). Indeed, the tandem tractor/quadaxle trailer is just below this range at 0.246 g.

A tridem tractor having its pusher axle down and in load-sharing position with the two drive axles does yield an improvement in roll stability for all three of the trailer types indicated. However, this

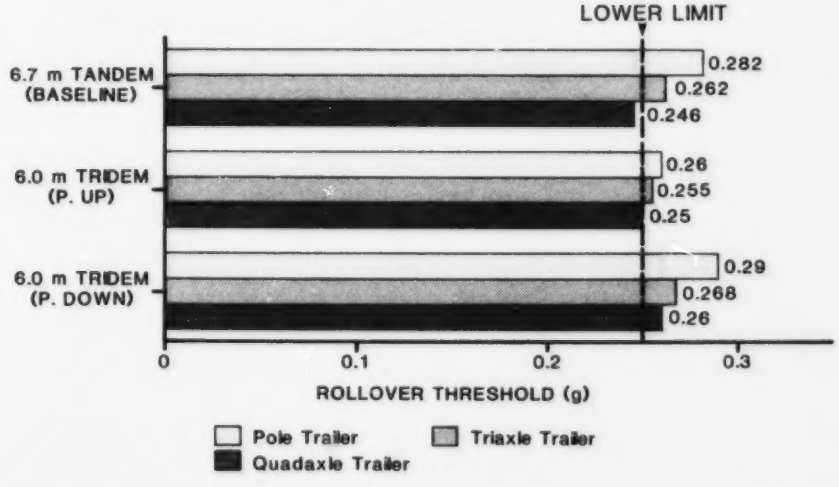


Figure 6. Influence of tractor type on rollover threshold with various trailers. The 6.7-m wheelbase tractor is a tandem unit and has a conventional track width of 2.4 m, whereas the 6.0-m wheelbase tridem tractor has a track width of 2.6 m. (P. refers to the add-on axle in the pusher location.)

gain diminishes when the pusher axle is lifted to enhance traction during the off-highway portion of the log-hauling cycle. This is a concern because the off-highway roads are of a lower standard than the provincially owned roadways, but this concern is somewhat alleviated because loaded trucks travel at slower speeds on off-highway roads.

The degree to which the rollover threshold diminishes when the pusher axle of the tridem tractor is lifted is important. With the pole and triaxle trailers, the tridem axle configuration exhibits a slightly lower threshold than the baseline tandem tractor counterparts. The tridem tractor in combination with the quadaxle trailer is the exception. Even with its pusher axle raised, this combination would have more roll stability than the baseline tandem tractor/quadaxle trailer vehicles of today.

Because the UMTRI static roll model cannot accommodate the tractor/jeep/pole trailer combination, and because these vehicles make up a significant portion of the log-hauling fleet, it was important that attempts be made to approximate their rollover threshold. Figure 7 illustrates that a tractor/quadaxle trailer, which has a known rollover threshold of 0.246 g, and a tractor/jeep/pole trailer have a similar height location of the centre of mass. Previous tilt-table measuring for rollover threshold done by Clark (6) includes these two combinations loaded to the dimensions permitted for long-log hauling (lower centre of mass of load). The findings in that report place the tractor/jeep/pole trailer rollover threshold at approximately 95% of the tractor/quadaxle trailer value. Extrapolated in terms of the tractor/quadaxle combination modelled by NRC, the tractor/jeep/pole trailer would then exhibit a rollover threshold of 0.234 g, the lowest of all the baseline combinations studied and therefore the least stable in terms of rollover.

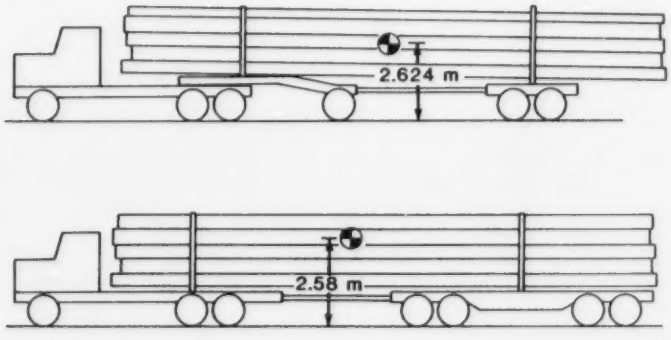


Figure 7. Comparison of centre of mass locations: Tractor/jeep/pole trailer (top) and tractor/ quadaxle trailer (bottom).

The rollover threshold modelling results illustrate the roll stability improvements offered by the wider tracking axles (2.6 m overall width). These axles allow the tridem tractor to be significantly more roll resistant, despite the increased load (see Appendix A), whereas a tridem tractor with conventional axle widths of 2.4 m is found to be unacceptable. Generally, the modelling results have identified the need to lower the centre of mass of these loaded vehicles, especially in cases where extra payload can be added by increasing the number of axles (see Appendix A). However, the fundamental configuration changes required to reduce the load centre of mass are beyond the scope of this project.

Directional Dynamics.

• *Rearward Amplification (RWA).* This analysis examined the influence of the tractor's design features on the lateral acceleration level and its amplification at the trailer and load centre of gravities over a wide range of steering input frequencies. For practical purposes, it is generally recognized that ergonomic constraints on human steering input effectively limit the upper range of frequencies to approximately 3 to 3.5 rad/s (i.e., steer inputs having approximately a two-second nominal period).

This analysis is useful for establishing:

- The lateral acceleration level at the centre of gravity of the vehicle elements during obstacle-avoidance situations on the highway.
- Whether or not the RWA is significantly greater than 1.0 in the practical range of steering frequencies (from 1.0 to 3.0 rad/s).

Figure 8 illustrates the relationship between the number of articulation points within the combination and the RWA. The pole trailer, because it has a single articulation point, has the least RWA; this trend holds true with the tridem tractor regardless of whether the pusher axle is in the up or down position. It is important to note that within the two-articulation-point vehicle category (triaxle or quadaxle trailer, and jeep/pole trailer), the jeep/pole trailer demonstrates a significantly higher RWA thus making it the least desirable of the combinations studied. The baseline tractor/jeep/pole trailer is a stable vehicle with respect to RWA but was found to have light dampening characteristics. Oscillatory response was another undesirable feature exhibited by all of the tractor/jeep/pole trailer configurations during the transient portion of the test maneuver.

In regard to the triaxle and quadaxle trailer configurations, the lateral acceleration of the tractor and dolly, for all cases, increases at relatively high frequencies (>3.5 rad/s) after falling off during

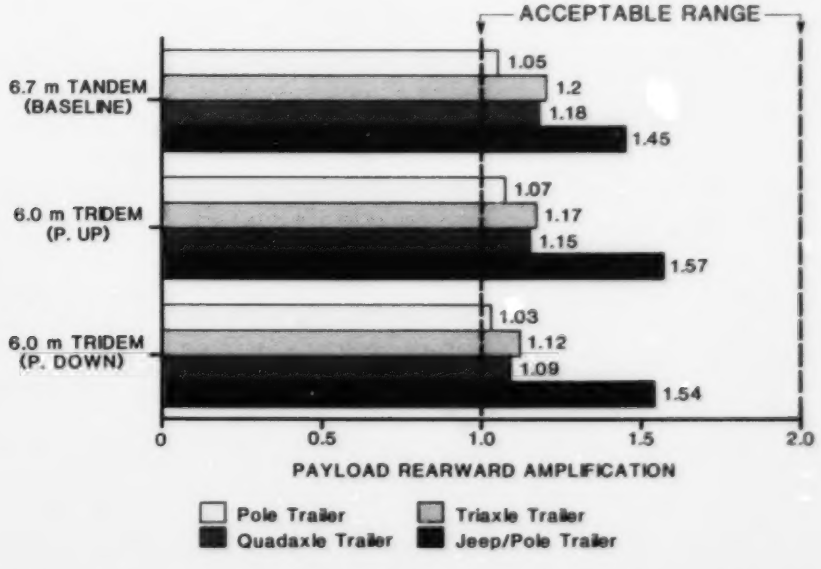


Figure 8. Influence of tractor type on the payload rearward amplification with various trailers at 90 km/h. The 6.7-m wheelbase tractor is a tandem unit and has a conventional track width of 2.4 m, whereas the 6.0-m wheelbase tridem tractor has a track width of 2.6 m. (P. refers to the add-on axle in the pusher location.)

the practical frequency range. This phenomenon causes a second RWA peak, which indicates the vehicle is unstable at high frequency. The RWA values are reasonable for the elements on those vehicle combinations that used a 6.0-m tridem axle tractor with a pusher axle in either the lowered or raised position, except for the jeep/pole trailer. The values are less than the values obtained from the baseline vehicle combination, with 6.7-m tandem axle tractors. These results would strengthen the decision to use the 6.0-m extended-width tractor in place of the tandem.

Further, it was found that the peak RWA values of the dolly elements on the quadaxle combination occur at frequencies lower than those of the triaxle combination. This result means that the quadaxle trailer can exhibit rollover tendencies, depending on the lateral acceleration level, during obstacle avoidance maneuvers with a moderate steering frequency.

The peak values of RWA and the corresponding frequency of a triaxle or a quadaxle trailer with the 6.0-m tridem axle tractor are not significantly affected by raising the pusher axle.

• *Transient Response Time.* The transient response of a vehicle can be judged by the time required to reach 90% of the steady-state lateral acceleration. This measure of response time is used as the principal performance measure in a ramp-step steer or J-turn maneuver. It is modelled at highway speeds (90 km/h) and is a measure of how quickly the vehicle will respond to operator steering input. The recognized standard operator reaction time is therefore the basis in establishing the acceptable performance criteria for the vehicles under study. External factors, such as complex traffic situations, and human factors like health disorders, are factored into this determination to yield an acceptable range of 0.3 s to a maximum of 1.7 s.

Figure 9 illustrates that, with the exception of the baseline 6.7-m tandem tractor/quadaxle trailer combination, all vehicles are within the acceptable range of transient response time performance. Before making recommendations for improving response time, this combination would require further detailed study.

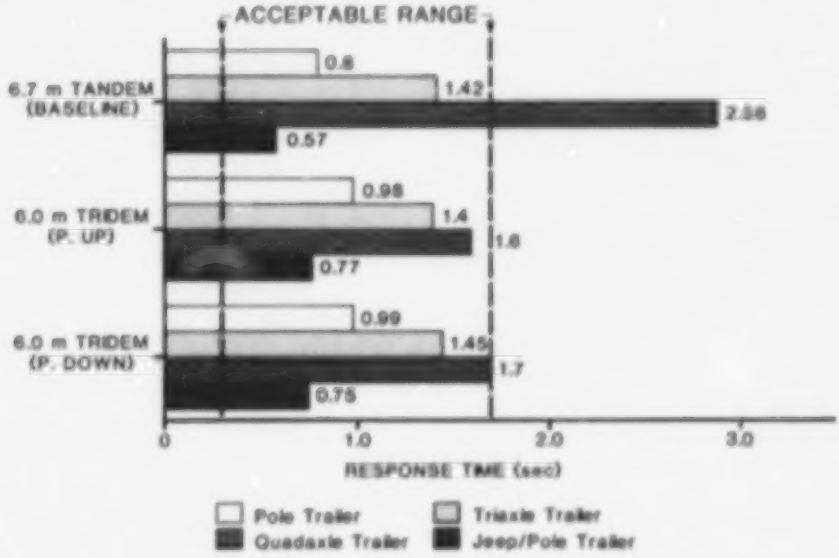


Figure 9. Influence of tractor type on transient response time with various trailers. The 6.7-m wheelbase tractor is a tandem unit and has a conventional track width of 2.4 m, whereas the 6.0-m wheelbase tridem tractor has a track width of 2.6 m. (P. refers to the add-on axle in the pusher location.)

In Figure 9, a comparison of the pusher axle in both the up and down positions indicates that lifting this axle has an insignificant effect on the acceptable response time for the tridem tractor.

• *Understeer Coefficient.* This criterion is used to determine the effects in steering performance that result when a variable is changed within a given tractor/trailer combination. In this case it was important to establish the magnitude of this change when the tridem axle group was modelled in relation to the baseline tandem tractor combinations.

The baseline tandem tractor/quadaxle trailer combination exhibits a greater than acceptable amount of understeering with a value of -4.2°/g, as illustrated in Figure 10.

Tridem tractors in combination with the jeep/pole trailer and triaxle trailer were also found to be understeering beyond the acceptable point of -4°/g.

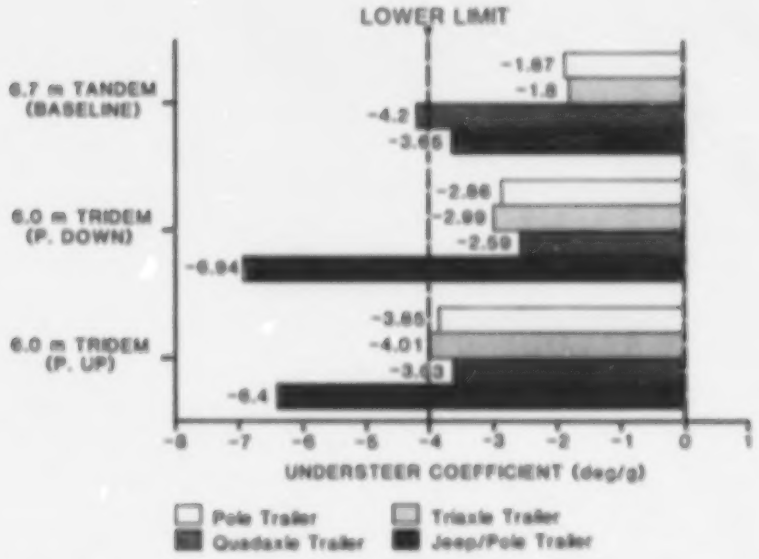


Figure 10. Influence of tractor type on the understeer coefficient with various trailers at 90 km/h. The 6.7-m wheelbase tractor is a tandem unit and has a conventional track width of 2.4 m, whereas the 6.0-m wheelbase tridem tractor has a track width of 2.6 m. (P. refers to the add-on axle in the pusher location).

• *Highspeed Offtracking Indicator.* The concern about highspeed offtracking stems from the recognition that the rear-most tires of a heavy vehicle generally follow a more outboard path than the steering tires of the tractor unit (e.g. in a lane-change maneuver). Figure 11 illustrates the significant influence that the tridem tractor has, in either condition, on increasing the highspeed offtracking indicator (except in the case of the jeep/pole trailer). In combination with either a triaxle or quadaxle trailer the tridem tractor (with pusher axle raised) is predicted to be beyond the acceptable range, and, in terms of the pole trailer, the tridem tractor is within the acceptable performance criteria. It is important to remember that when the pusher axle is raised the vehicle is considered to be in the off-highway mode where speed is much less than 90 km/h.

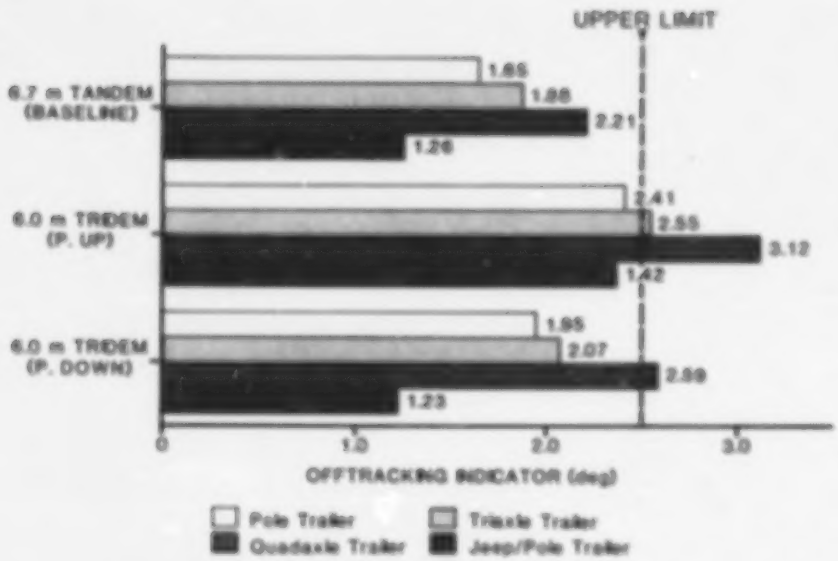


Figure 11. Influence of tractor type on the highspeed offtracking with various trailers at 90 km/h. The 6.7-m wheelbase tractor is a tandem unit and has a conventional track width of 2.4 m, whereas the 6.0-m wheelbase tridem tractor has a track width of 2.6 m. (P. refers to the add-on axle in the pusher location.)

CONCLUSIONS

Phase I included a literature search and a hardware search of tridem axle technology, and a traction and dynamic performance analysis of existing and proposed log-hauling combinations for both tandem and tridem axle tractors.

Literature and Hardware Searches

The literature search identified little previous research in the use of tridem axle groups, and no North American axle manufacturer produces a tridem axle drive group with balanced interaxle torque distribution. Available European tridem drive axle technology is not appropriate for the dual wheel application common to North American Class 8 tractors.

Hardware to build a tridem tractor unit with an airlift non-driven axle located forward of a tandem drive axle assembly is available and compatible with existing equipment. The technology is also available to ensure that equalized axle loading with the tridem group is achieved within the RTAC guidelines (3); however, this remains to be verified by field testing.

Traction Gradeability Study

The tractive assessments done by VSDC (4) demonstrated dramatic gradeability improvements of 56.7% and 37.3% for lift axle and tridem drive axle groups respectively, over conventional tandem drive tractor combinations of comparable GVW. The tandem drive tractor with the airlift axle in the

raised position achieved a considerable margin in gradeability improvement over the other tridem option with the three driven axles.

Dynamic Performance Analysis

Based on the results obtained from the computer simulation models (1), the following conclusions can be drawn:

- The predicted static rollover thresholds of all baseline vehicle combinations with critical values (around 0.3 g) indicate that improvements are required in one or more of the baseline design parameters that significantly affect the vehicles' rollover thresholds (for example the vehicle overall width, load centre of gravity height, bunk lash, etc.).

- The rollover thresholds were significantly reduced when tridem axle tractors were used in place of tandem axle tractors because of the increased loads and their centre of gravity heights, which in turn resulted in higher roll moments than the restoring moments produced by the additional axle. This result clearly shows that the rollover thresholds of these vehicles are very sensitive to load centre of gravity height and weight. Roll stability can be significantly improved, however, by designing a tridem tractor with wide-track axles (2.6 m) in place of standard-width axles (2.4 m).

- The overall vehicle handling characteristics of a tractor towing a pole trailer, jeep/pole trailer, triaxle trailer, or quadaxle trailer were different because of the major differences in their design and loading features. Therefore, no general conclusion with respect to the results of the time history and frequency response studies can be made. However, conclusions can be made for each vehicle group having similar design features.

  The baseline tractor/pole trailer exhibited understeering characteristics and was stable, but its handling performance was not as good as the tridem tractor with the 6.0-m, wheelbase. No RWA problems were revealed with the tridem tractor (pusher axle down), especially with respect to the load centre of gravity. Lifting the pusher axle on a 6.0-m wheelbase tridem tractor did not result in stability problems. In general, the tridem axle tractor with the pusher axle down or lifted is directionally stable.

  The baseline tractor/jeep/pole trailer combinations, with 6.7-m wheelbase tandem tractors, were both understeered and stable. However, the vehicle system exhibited lightly damped characteristics and directional oscillations. When a tridem axle tractor (pusher axle down) was used, the oscillations of the vehicle elements exhibited less of an overshooting problem. (This was caused mainly by the increased vehicle system damping coefficient, attributable to a reduction of its understeer level.) The steady-state lateral acceleration values of these vehicles were greater than those of the tandem axle or tridem axle tractor with the pusher axle lifted. The response times for the tandem and tridem tractors were not significantly different from each other. The tractor/jeep/pole trailer exhibited high RWA within the practical rapid steering frequency range (close to 3 rad/s). The RWA problem was less severe when the pusher axle of the 6.0-m tridem axle was down.

  The baseline tractor/triaxle and quadaxle trailer combinations (tandem tractor) were stable in terms of the directional dynamics; however, the relatively low rollover threshold of these combinations is a concern. The triaxle trailer vehicle combination exhibited slight understeering, while the quadaxle trailer vehicle combination exhibited less understeering. The response time of the quadaxle trailer was greater than that of the triaxle trailer, because of the larger load weight and its high yaw moment of inertia. When combined with the 6.0-m tridem axle tractor, with pusher axle lifted, neither type of trailer exhibited unstable behaviour. Lifting the pusher axle of the 6.0-m tridem axle tractor did not result in a significant change in the RWA and its corresponding frequency.

- The baseline tractor/jeep/pole trailer and tractor/quadaxle trailer are not recommended and their use should be discouraged because of their undesirable directional behaviour.

- The results of this analysis highlight vehicle dynamic deficiencies with two of the existing baseline combinations, i.e. the tractor/jeep/pole trailer and the tractor/quadaxle trailer. The deficiencies were also evident in the modelling of the tridem tractor with these same two trailers, and the triaxle trailer. However, the pole trailer, when studied with any of the tractor options, was found to be acceptable, and it is here that the tridem tractor offers its greatest potential in terms of improving the safety-related performance of 6- and 7-axle log-hauling vehicles. The existing 6-axle tractor jeep/pole trailer has been found to be dynamically undesirable, in part because of its additional articulation point but also because of its relatively low rollover threshold. The tridem tractor/pole trailer combination is also a 6-axle unit but has neither of these critical deficiencies, and, by comparison, is a considerable improvement. The single articulation point of a tridem tractor/pole trailer is similarly attractive in comparison to the baseline two-articulation-point tandem tractor/triaxle trailer vehicle, which is another 6-axle combination. Although not studied in this project, the tridem tractor/tridem pole trailer 7-axle combination offers a potential alternative to the 7-axle baseline tractor/quadaxle trailer, which was also found to exhibit undesirable performance.

- On multi-articulated 6-axle log hauling configurations a single axle and a tandem axle are combined in the trailing units. Examples of this are jeep/pole trailers, triaxle trailers, and dog loggers. The single-axle chassis is also the additional point of articulation and the elimination of this chassis reduces the vehicle to a single articulated combination which has been shown to be more dynamically desirable in this study. However, the reduction in payload capacity caused by the removal of this single axle has made these single articulation vehicles unattractive. A tridem tractor combined with a pole trailer would provide a payload recovery by the addition of the extra axle and would not have the undesirable performance associated with the multi-articulated configurations. Furthermore, this additional axle would be part of an equalized load-sharing suspension which provides the additional benefits for a more balanced distribution of brake forces.

- In terms of safe handling, a single-articulated vehicle offers the driver greater vehicle control with respect to emergency braking, emergency object-avoidance maneuvers, and reversing on downgrades (i.e. after vehicle spinout).

RECOMMENDATIONS

With Phase I of the study now complete, a number or recommendations can be made:

1. In terms of gradeability, the non-driven airlift axle used in conjunction with a tandem drive axle assembly to form the tridem grouping is the recommended choice of the two tridem options studied. However, some provincial jurisdictions do not allow the use of lift axles; where this is the case, the tridem drive tractor option offers significant benefits and should be considered as the second choice.

2. A tridem tractor is recommended for use in single-articulation-point combinations (i.e. with pole trailers) as an alternative to tandem tractor/jeep/pole trailer units.

3. It is recommended that application be made to the British Columbia Ministry of the Solicitor General requesting that a special permit be issued to test a tridem tractor/pole trailer combination. Such a test would require demonstration of load sharing among the tridem axles prior to on-highway operation. In addition, should a tilt-table be available, a static rollover threshold trial is recommended as a preliminary means of assessing the accuracy of the computer-simulated rollover predictions.

4. Recommended specifications for test tractors include:

   Option 1 - Tridem tractor with air-lift axle.
   - Wide-track tandem drive axles with an airlift axle in the pusher location.
   - Tandem drive axles and related suspension with a weight rating of 23 000 kg to accept the additional load when the pusher axle is lifted when off-highway.
   - A pusher axle suspension of pneumatic design with an automatic load-sharing control system.
   - Lift controls for the pusher axle located outside of the tractor's cab.

   Option 2 - Tridem tractor with tridem drive axle group.
   - Wide-track tridem drive axles with equalized load sharing suspension.
   - Tractor to be equipped with anti-lock brake (ABS) automatic spin regulation (ASR) systems.

5. The vehicle dynamics study presents a first-order estimate of the rollover threshold and directional stability of the vehicles examined. The results obtained for the time histories of Yaw Plane Response (steady-state) are valid only for low lateral acceleration maneuvers (less than 0.15 g). Before any final decision is made on the acceptability for service of the vehicles which exhibited stable behaviour and reasonable rollover threshold, it is recommended they be subjected to field tests to confirm the computed performance characteristics.

LIST OF REFERENCES

1. El-Gindy, M. and Woodrooffe, J.H.F., *Study of Rollover Threshold and Directional Stability of Log Hauling Trucks*, National Research Council of Canada, Division of Mechanical Engineering, Vehicle Dynamics Laboratory, Ottawa, 1990/02, 200 pp., TR-VDL-002, NRC No. 31274.

2. British Columbia Ministry of Transportation and Highways, Commercial Transport Act, Chapter 55, Victoria, B.C., October 1988.

3. Roads and Transportation Association of Canada, *Vehicle Weights and Dimensions Study: Technical Steering Committee Report*, Ottawa, November 1986, 60 pp.

4. Preston-Thomas, J. and Wong, J.Y., *The Gradeability of Logging Trucks, Final Report*, Vehicle Systems Development Corporation, Ottawa, May 1989, 179 pp.

5. Robert Bosch GmbH, *Automotive Handbook*, U. Adler et al (eds.), Stuttgart, 1986, 2nd English edition based on the 20th German edition.

6. Clark, Marvin, *Static Roll-Stability Evaluations of Long-Log Trucks*, Forest Engineering Research Institute of Canada, Vancouver, B.C., 1988, 8 pp., Technical Note No. TN-124.

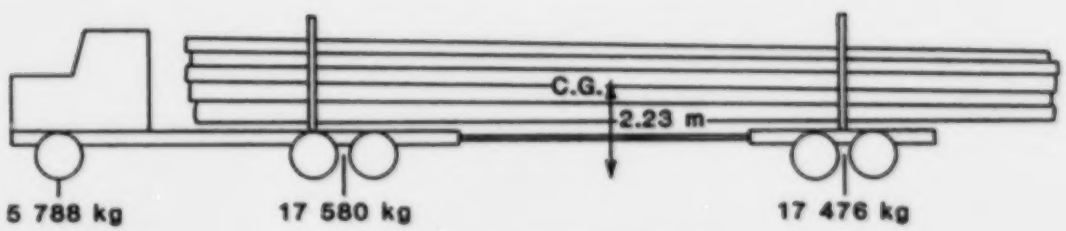
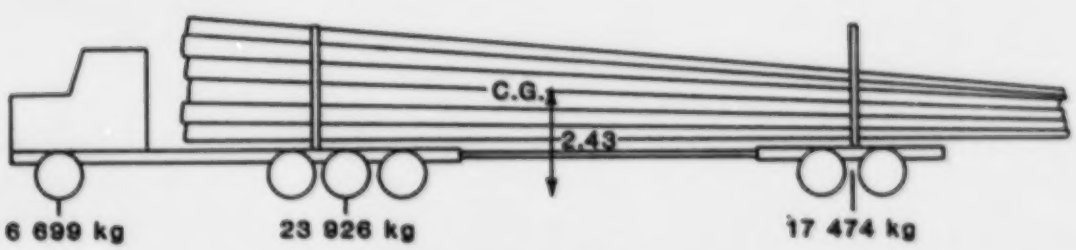
APPENDIX A

Representations of the Block Load Densities as Applied to Various Log-Hauling Vehicle Combinations

Representations of the Block Load Densities as Applied to Various Log-Hauling Vehicle Combinations

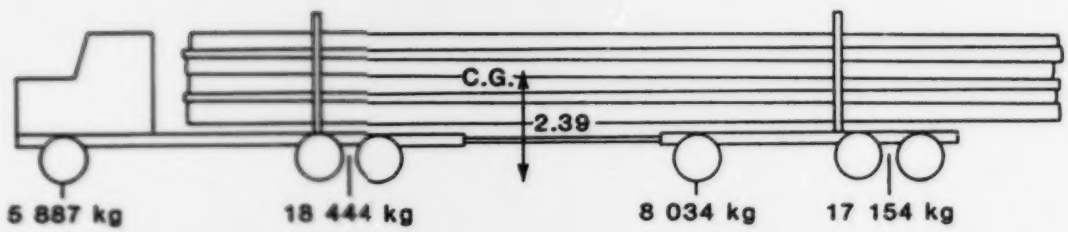
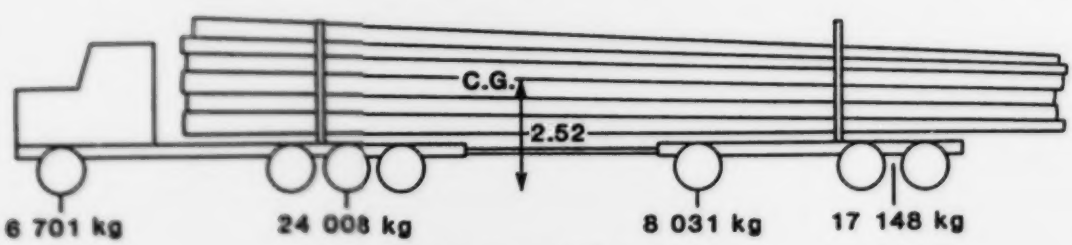
Tractor/Pole Trailer

Vehicle specifics	Tandem [a]	Tridem [b]
Rollover threshold (g's)	0.282	0.29
Load height front (m)	3.30	4.15
Load height rear (m)	2.58	2.28
Load centre of gravity height (m)	2.23	2.43 [c]
Gross vehicle weight (kg)	40 844	48 099

[a] Tandem axle tractor with 2.4-m (8-ft) axle width.
[b] Tridem axle tractor with 2.6-m (8.5-ft) axle width.
[c] C.G. raised 20 cm when loaded to the capacity of a tridem axle group.

Tandem Tractor/Pole Trailer

Tridem Tractor/Pole Trailer

Tractor/Triaxle Trailer

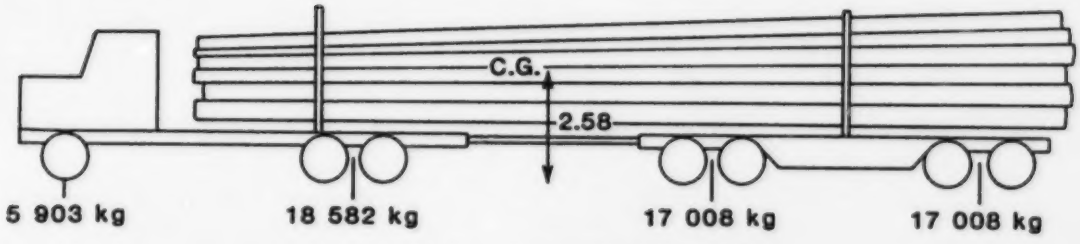
Vehicle specifics	Tandem [a]	Tridem [b]
Rollover threshold (g's)	0.262	0.268
Load height front (m)	3.30	4.01
Load height rear (m)	3.30	3.05
Load centre of gravity height (m)	2.39	2.52 [c]
Gross vehicle weight (kg)	49 519	55 888

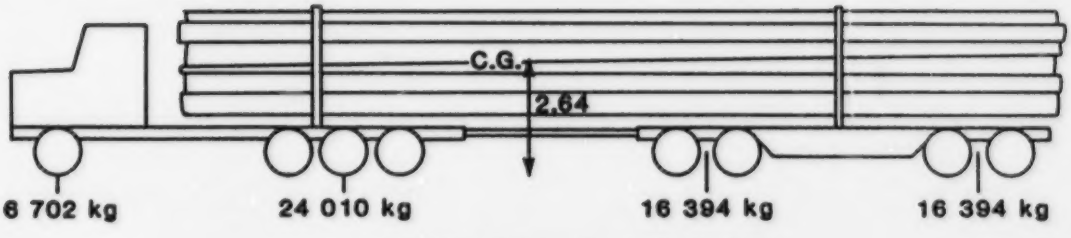
[a] Tandem axle tractor with 2.4-m (8-ft) axle width.
[b] Tridem axle tractor with 2.6-m (8.5-ft) axle width.
[c] C.G. raised 13 cm when loaded to the capacity of a tridem axle group.

Tandem Tractor/Triaxle Trailer

Tridem Tractor/Triaxle Trailer

Tractor/Quadaxle Trailer

Vehicle specifics	Tandem [a]	Tridem [b]
Rollover threshold (g's)	0.246	0.26
Load height front (m)	3.15	3.86
Load height rear (m)	4.15	3.75
Load centre of gravity height (m)	2.58	2.64 [c]
Gross vehicle weight (kg)	58 501	63 500

[a] Tandem axle tractor with 2.4-m (8-ft) axle width.
[b] Tridem axle tractor with 2.6-m (8.5-ft) axle width.
[c] C.G. raised 6 cm when loaded to the capacity of a tridem axle group.



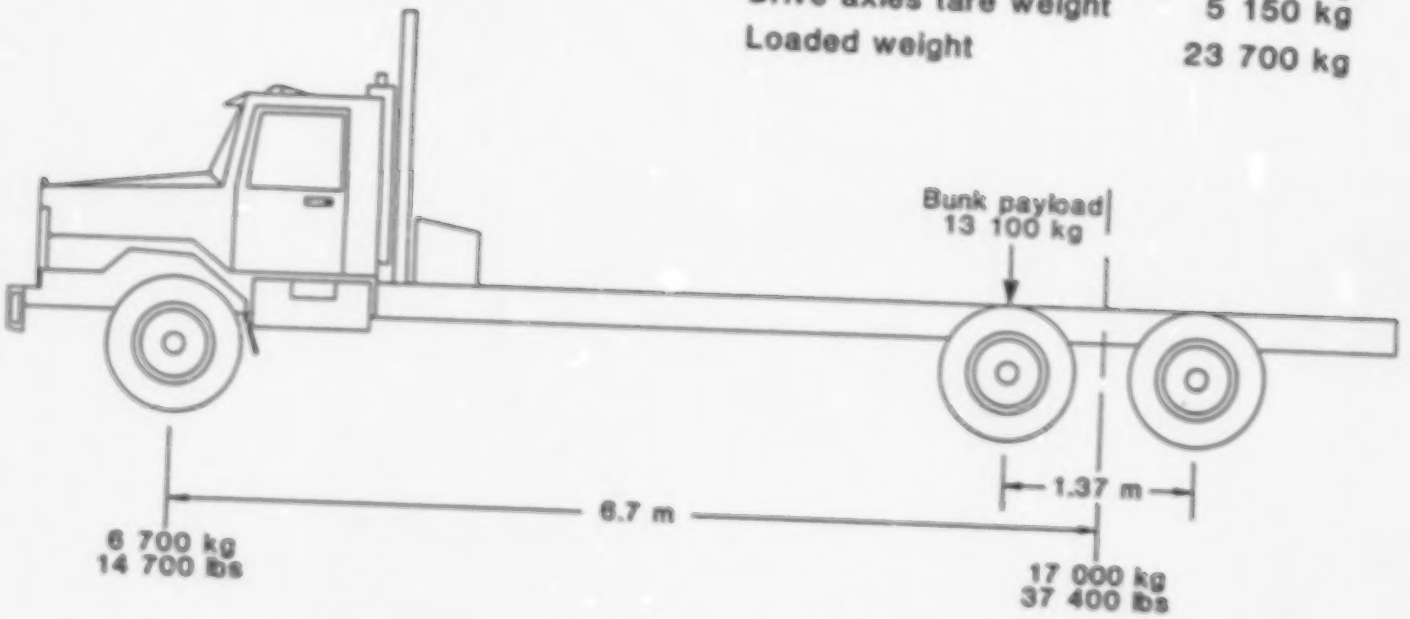
Tandem Tractor/Quadaxle Trailer

Tridem Tractor/Quadaxle Trailer

APPENDIX B

Subject Tractor Units for Field Testing

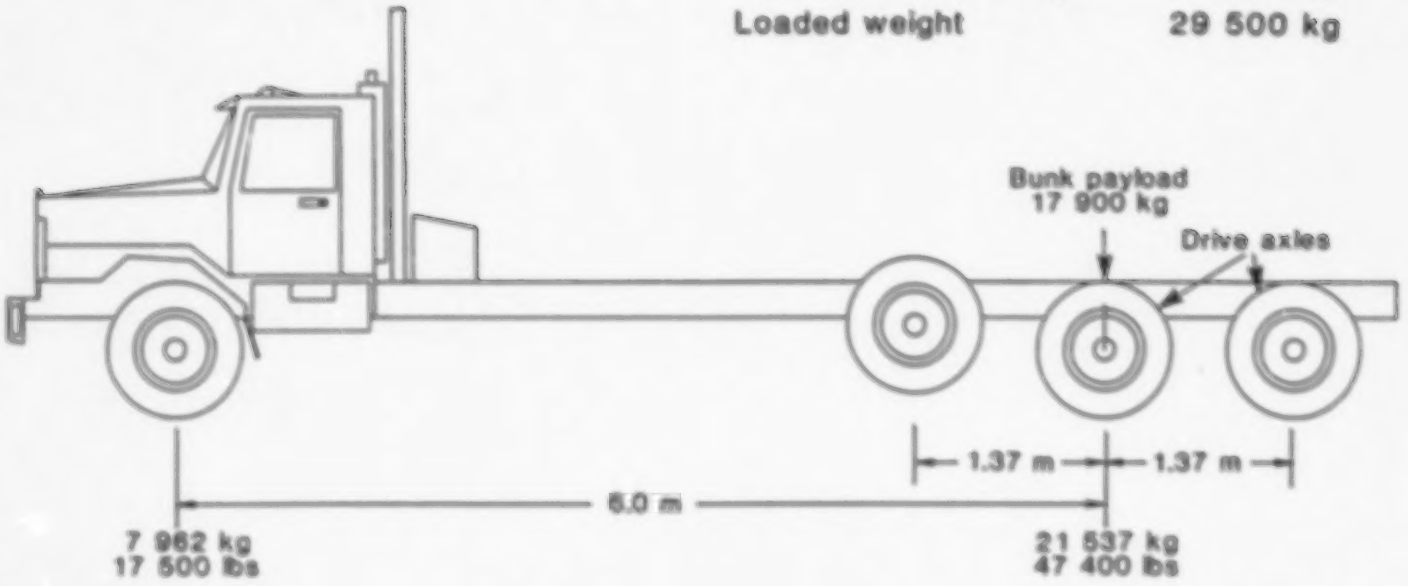
Existing Tractor Unit

Tare weight	10 600 kg
Steering axle tare weight	5 450 kg
Drive axles tare weight	5 150 kg
Loaded weight	23 700 kg



Off-Highway Traction Mode

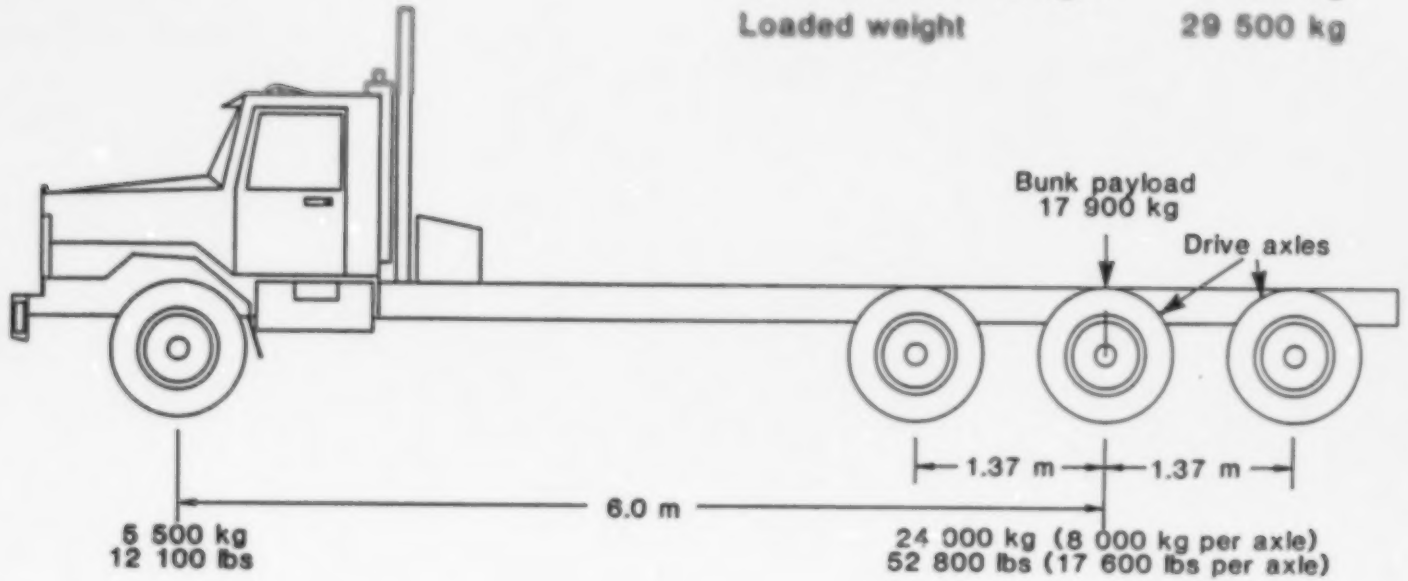
Tare weight	11 600 kg
Steering axle tare weight	5 500 kg
Drive axles tare weight	6 100 kg
Loaded weight	29 500 kg



Note: The wheelbase dimension becomes shorter when the tractor is converted to a tridem configuration. The original axle locations have not changed; however, the reference location for a tridem grouping moves forward to the centre of the middle axle.

On-Highway Mode

Tare weight	11 600 kg
Steering axle tare weight	5 500 kg
Drive axles tare weight	6 100 kg
Loaded weight	29 500 kg



Note: The wheelbase dimension becomes shorter when the tractor is converted to a tridem configuration. The original axle locations have not changed; however, the reference location for a tridem grouping moves forward to the centre of the middle axle.

APPENDIX C

Organizations Consulted During the Hardware Search

Organizations Consulted During the Hardware Search

Hendrickson Manufacturing Ltd.
Ingersol Axle
Neway Operations, Truck Products Division
Dana Corporation
Hi Steer Ltd.
ASTL Inc.
Rinker Industries Inc.
Eaton Corporation (Axle and Brake Division)
Rockwell International Corporation (Automotive Operations)
Consolidated Concrete Ltd.
Premay Heavy Haulers Inc.
Scona Spring and Trailer
GKN Automotive Components
Mack Trucks Inc.
Kenworth Truck Company
Freightliner Truck Corporation
Fabco Ltd. (Division of Kelsey-Hayes)
Dyner Corporation - Granning Div.
Ross Gear Division, TRW
Chalmers Suspension International Ltd.
Turner Suspensions Ltd.
Whelan Axle Systems
Aspen Trailers
Danco Ltd.
Rotec Trailer
Vanderwell Contracting 1971 Ltd.
Clawson Concrete Ltd.
Paccar Technical Centre
Western Star Trucks Inc.
Ministry of Transport, Ontario
Motor Transport Branch, Alberta Transportation
Ministry of Transport, Saskatchewan
Giant Trucks Inc.
Saab-Scania of America, Inc.
Mercedes-Benz Trucks Inc.
Walter Trucks Ltd.
Pacific Truck and Trailer Ltd.
Vancouver Axle & Frame Ltd.

APPENDIX D

Log-Hauling Routes with Challenging Grades

Log-Hauling Routes with Challenging Grades

Road Segments

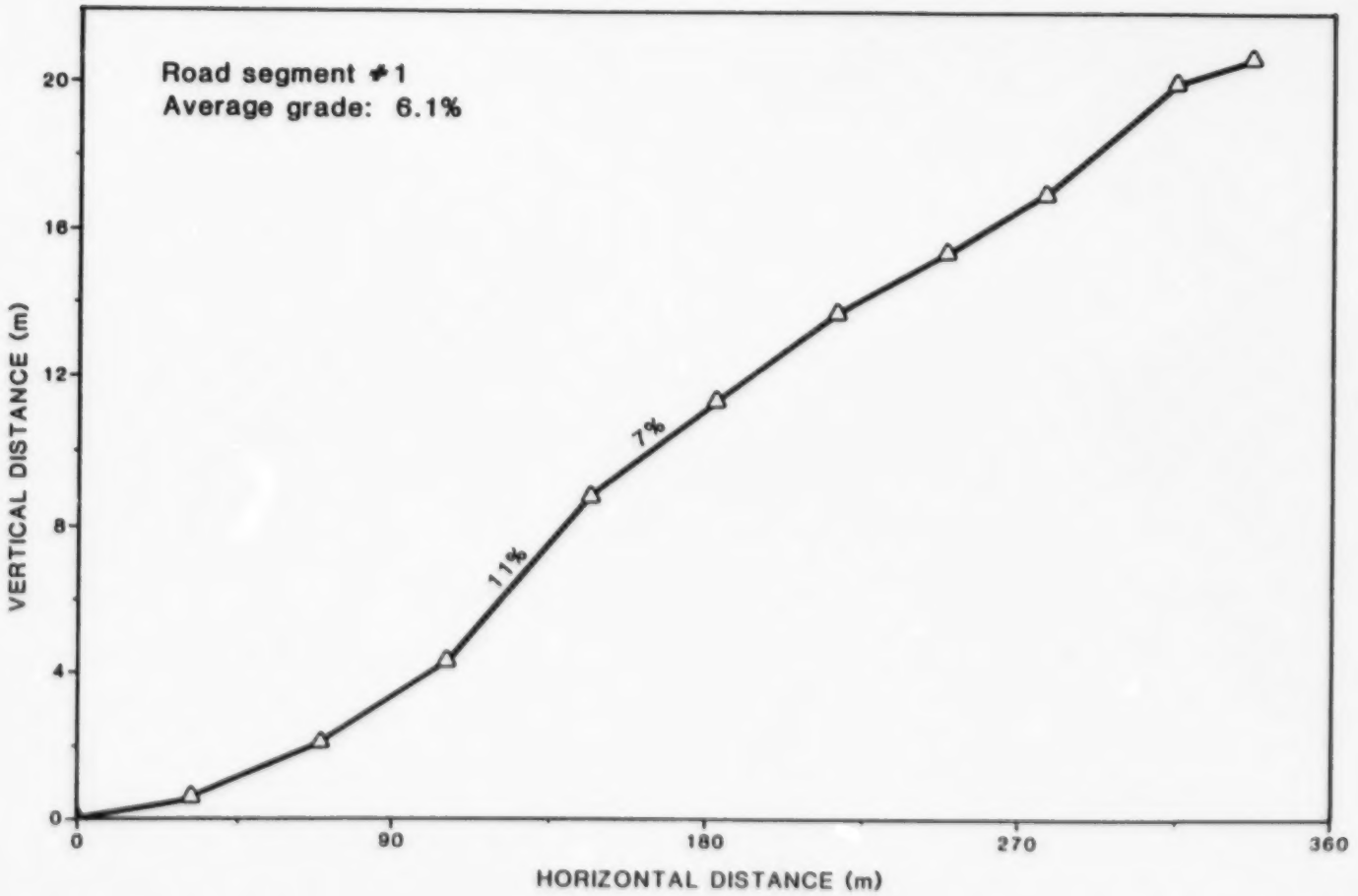
Three road segments were surveyed near Williams Lake. The first segment is 340 m in length with an average grade of 6.1% adverse, i.e. the loaded vehicle would be travelling uphill. The second segment is 270 m in length and has an average grade of 8.4%. The third segment has a length of 1060 m with an average grade of 5.8%.

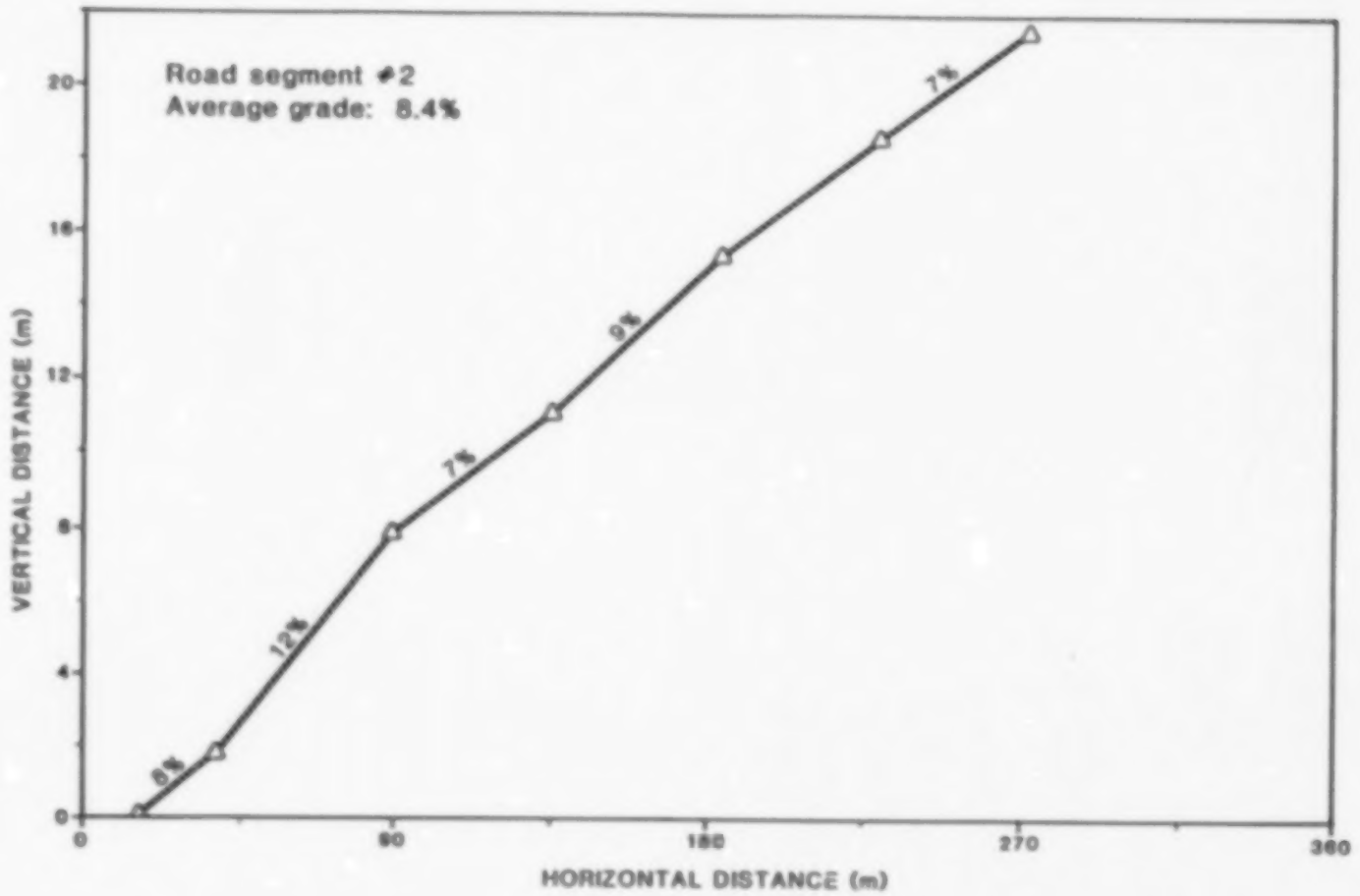
Segment	Station	Horizontal distance (m)	Azimuth (degrees)	Slope (%)	Slope distance (m)	Vertical distance (m)	Total vertical (m)
No. 1	0.0						
		32.0	274	2	32	0.64	0.64
	32.0						
		37.0	295	4	37	1.48	2.12
	69.0						
		36.9	305	6	37	2.21	4.33
	105.9						
		40.8	321	11	41	4.49	8.82
	146.7						
		35.9	325	7	36	2.51	11.33
	182.6						
		34.9	312	7	35	2.44	13.77
	217.5						
		32.0	297	5	32	1.60	15.37
	249.4						
		27.9	273	6	28	1.67	17.04
	277.4						
		37.9	248	8	38	3.03	20.07
	315.3						
		22.0	245	3	22	0.66	20.73
	337.3						
No. 2	0.0						
		17.0	263	0	17	0.00	0.00
	17.0						
		21.9	292	8	22	1.75	1.75
	38.9						
		50.6	317	12	51	6.07	7.82
	89.6						
		45.9	319	7	46	3.21	11.03
	135.5						
		48.8	328	9	49	4.39	15.42
	184.3						
		45.9	306	7	46	3.21	18.63
	230.2						
		41.9	297	7	42	2.93	21.56
	272.1						

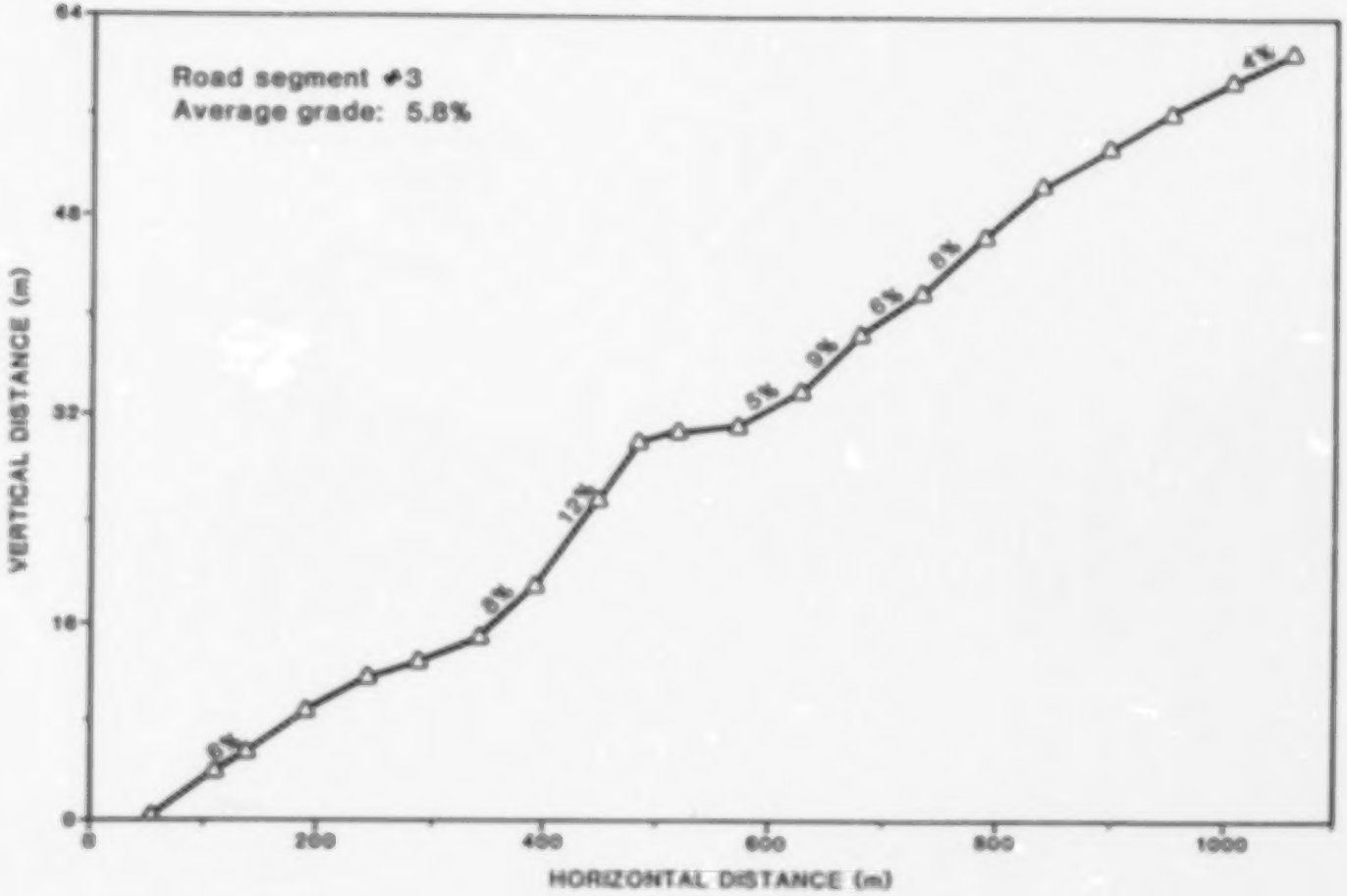
...Table continued on next page

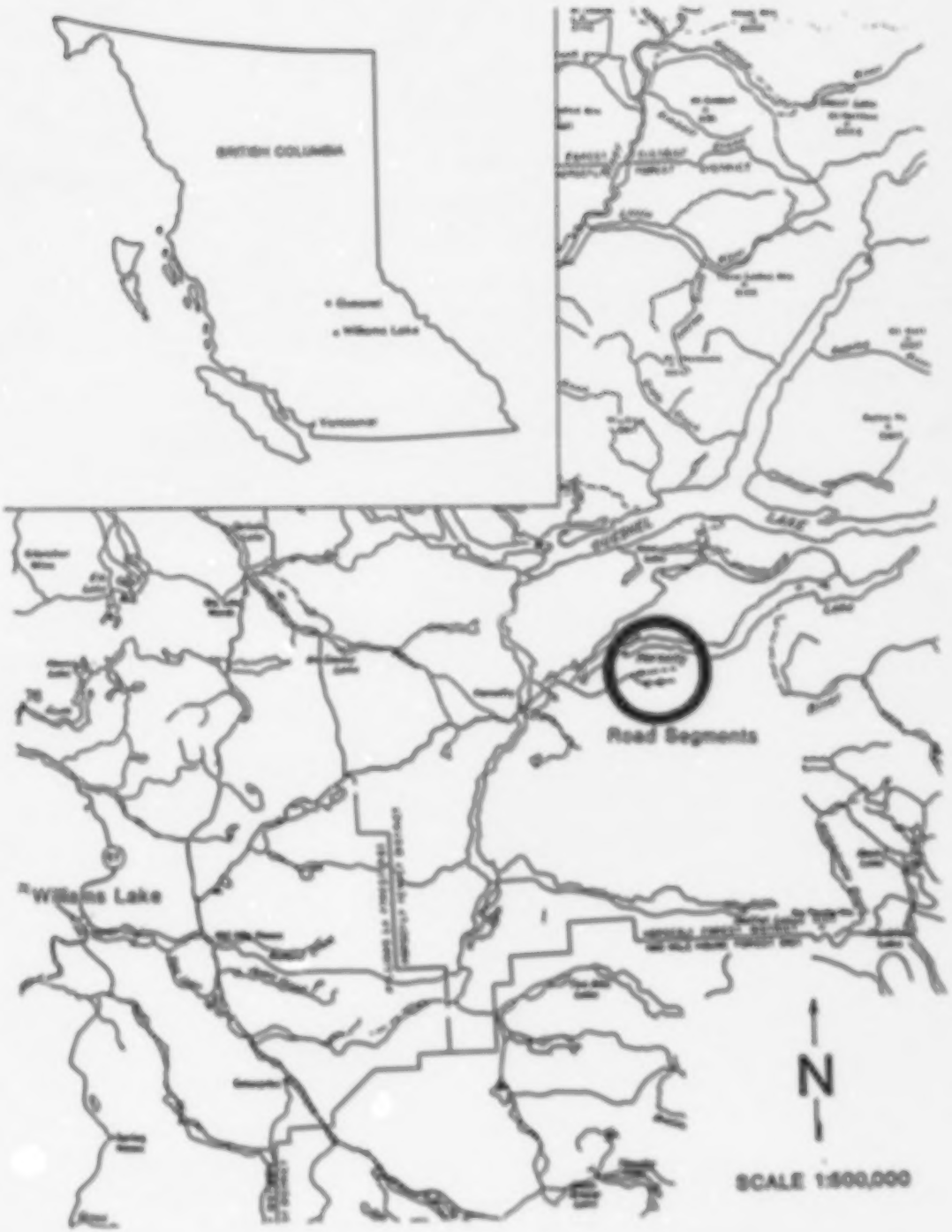
Appendix D, continued

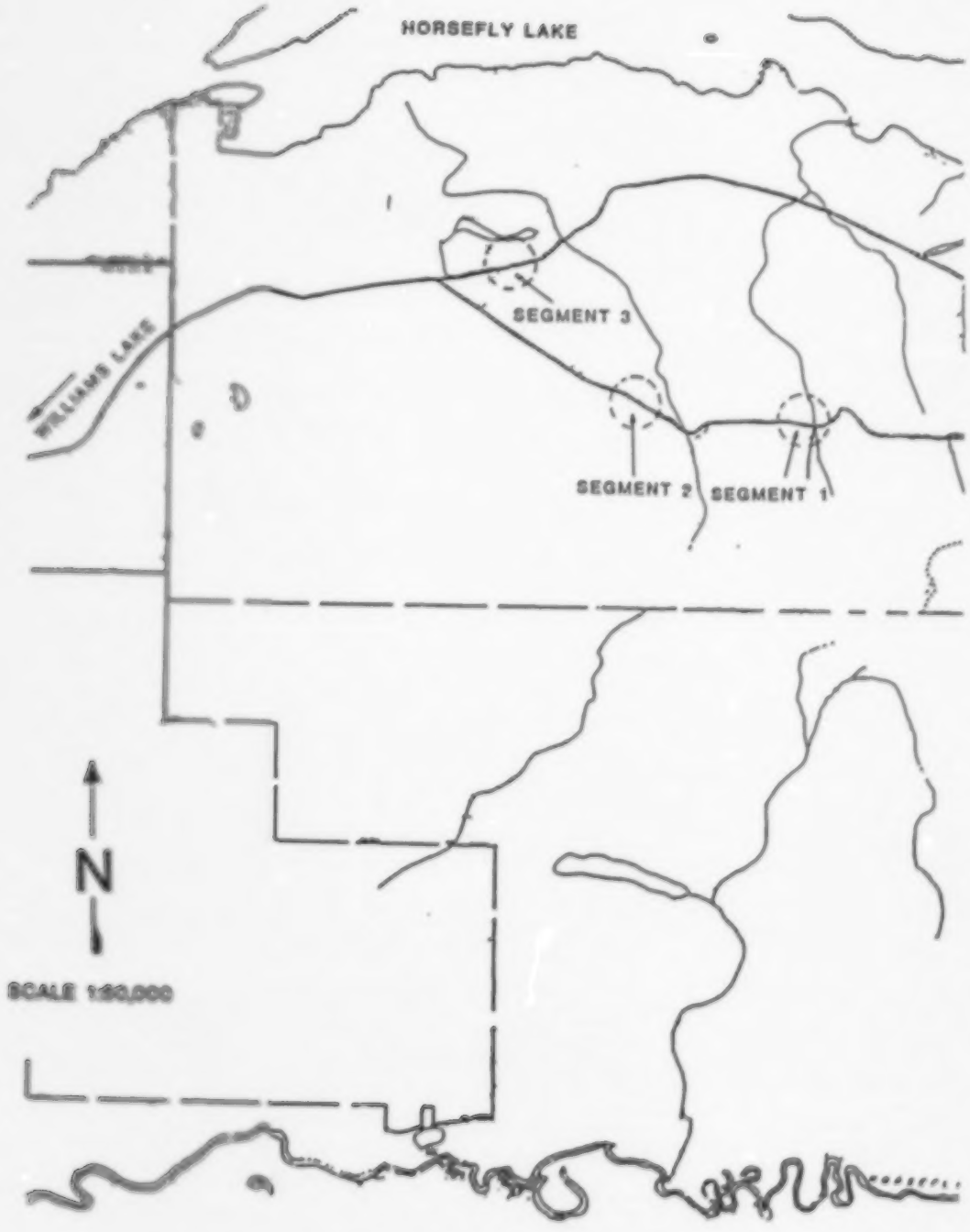
Segment	Station	Horizontal distance (m)	Azimuth (degrees)	Slope (%)	Slope distance (m)	Vertical distance (m)	Total vertical (m)
No. 3	0.0						
		55.0	225	1	55	0.55	0.55
	55.0						
		53.9	231	6	54	3.24	3.79
	108.9						
		27.9	244	6	28	1.67	5.46
	136.9						
		52.9	267	6	53	3.18	8.64
	189.8						
		54.9	272	5	55	2.75	11.39
	244.7						
		43.0	256	3	43	1.29	12.68
	287.7						
		55.0	245	4	55	2.20	14.88
	342.6						
		50.8	245	8	51	4.08	18.96
	393.5						
		54.6	230	12	55	6.60	25.56
	448.1						
		36.7	234	12	37	4.44	30.00
	484.8						
		33.0	269	2	33	0.66	30.66
	517.8						
		55.0	287	1	55	0.55	31.21
	572.8						
		54.9	261	5	55	2.75	33.96
	627.7						
		52.8	258	9	53	4.77	38.73
	680.5						
		54.9	265	6	55	3.30	42.03
	735.4						
		54.8	272	8	55	4.40	46.43
	790.3						
		53.8	269	8	54	4.32	50.75
	844.1						
		54.9	268	5	55	2.75	53.50
	899.0						
		54.9	252	5	55	2.75	56.25
	954.0						
		54.9	249	5	55	2.75	59.00
	1008.9						
		54.0	248	4	54	2.16	61.16
	1062.9						


Road segment #1
Average grade: 6.1%
VERTICAL DISTANCE (m)
HORIZONTAL DISTANCE (m)
0
4
8
12
16
20
0
90
180
270
360
11%
7%


Road segment #2
Average grade: 8.4%
VERTICAL DISTANCE (m)
HORIZONTAL DISTANCE (m)
0
4
8
12
16
20
90
180
270
360
6%
12%
7%
9%
7%


Road segment #3
Average grade: 5.8%
VERTICAL DISTANCE (m)
HORIZONTAL DISTANCE (m)
0
16
32
48
64
0
200
400
600
800
1000
6%
12%
5%
6%
6%
6%
4%

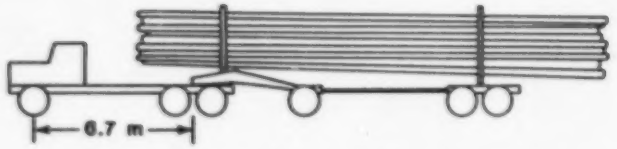

BRITISH COLUMBIA
Williams Lake
Road Segments
Williams Lake
N
SCALE 1:500,000


HORSEFLY LAKE
SEGMENT 3
WILLIAMS LAKE
SEGMENT 2
SEGMENT 1
N
SCALE 1:50,000

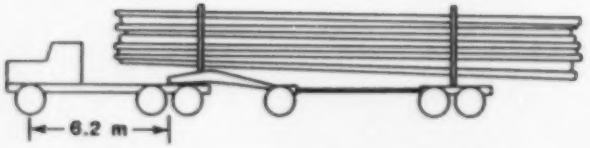
APPENDIX E

Log-Hauling Vehicle Combinations Analyzed for Dynamic Performance and Static Roll Stability

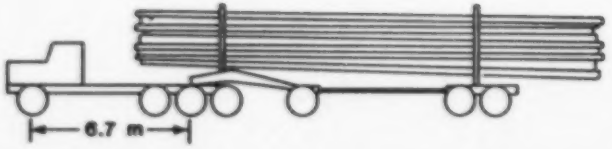
6.7-m and 6.2-m Tractor/Jeep/Pole Trailer Combinations



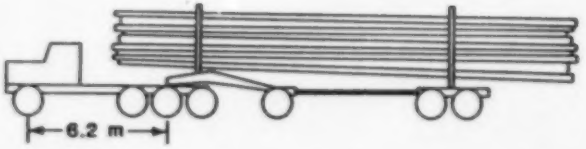
6.7-m Tandem Tractor/Jeep/Pole Trailer



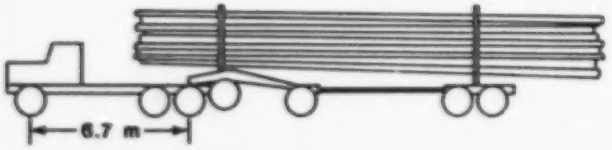
6.2-m Tandem Tractor/Jeep/Pole Trailer



6.7-m Tridem Tractor/Jeep/Pole Trailer (Tag axle down)



6.2-m Tridem Tractor/Jeep/Pole Trailer (Tag axle down)

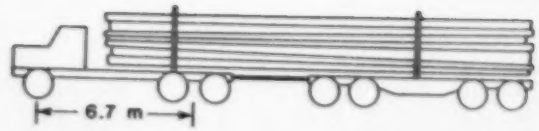


6.7-m Tridem Tractor/Jeep/Pole Trailer (Tag axle lifted)

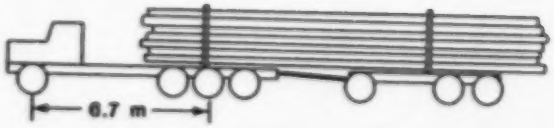
6.2-m Tridem Tractor/Jeep/Pole Trailer (Tag axle lifted)

6.7-m Tractor/Triaxle and Quadaxle Trailer Combinations

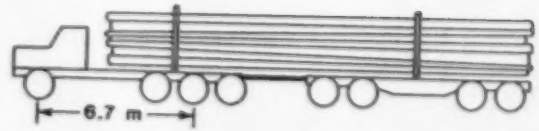
6.7-m Tandem Tractor/Triaxle Trailer



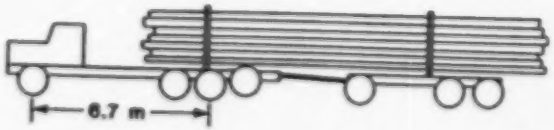
6.7-m Tandem Tractor/Quadaxle Trailer



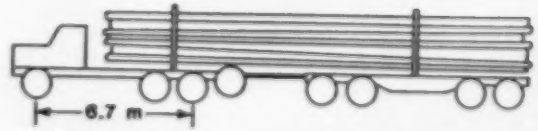
6.7-m Tridem Tractor/Triaxle Trailer (Tag axle down)



6.7-m Tridem Tractor/Quadaxle Trailer (Tag axle down)

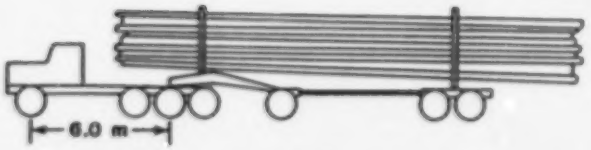


6.7-m Tridem Tractor/Triaxle Trailer (Tag axle lifted)



6.7-m Tridem Tractor/Quadaxle Trailer (Tag axle lifted)

Proposed 6.0-m Tractor/Trailer Combinations

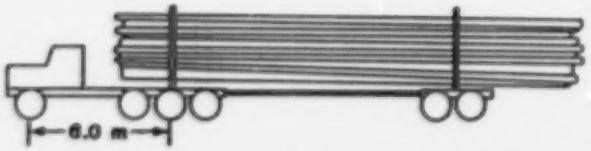


6.0-m Tridem Tractor/Jeep/Pole Trailer (Pusher down)

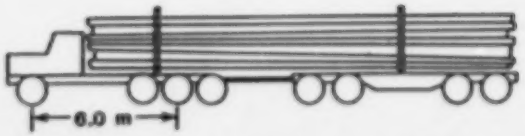
6.0-m Tridem Tractor/Triaxle Trailer (Pusher down)

6.0-m Tridem Tractor/Jeep/Pole Trailer (Pusher lifted)

6.0-m Tridem Tractor/Triaxle Trailer (Pusher lifted)

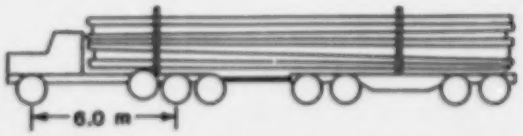


6.0-m Tridem Tractor/Pole Trailer (Pusher down)



6.0-m Tridem Tractor/Quadaxle Trailer (Pusher down)

6.0-m Tridem Tractor/Pole Trailer (Pusher lifted)



6.0-m Tridem Tractor/Quadaxle Trailer (Pusher lifted)